

THEORETICAL AND EXPERIMENTAL INVESTIGATION OF
THE EFFECT OF DYE ON SOLAR DISTILLATION

By

JULI EDNA ALFARONE

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LIST OF SYMBOLS

A_a	Area of still cover, ft^2
A_g	Area of glass cover, ft^2
A_w	Area of water surface, ft^2
b	Intercept of evaporation lines in Figure 4 through 11, $\text{lb}/\text{ft}^2\text{-day}$
c	Concentration of dry, ppm
c_p	Specific heat, $\text{Btu}/\text{lb}^\circ\text{F}$
D	Diffusion vapor equivalent DOL, $\text{lb}/\text{ft}^2\text{-hr}$
D_{12}	Binary diffusion coefficient, ft^2/hr
E	Factor given by equation (10), $\text{lb}/\text{ft}^2\text{-day}$
E_a, E_b	Arrhenius and generalized shape factors
g	Acceleration due to gravity, ft/sec^2
Gr	Grashof Number
h_a	Convective heat transfer coefficient from water surface to glass cover, $\text{Btu}/\text{ft}^2\text{-hr}^\circ\text{F}$
h_{conv}	Free convection heat transfer coefficient, $\text{Btu}/\text{ft}^2\text{-hr}^\circ\text{F}$
h_{12}	Conductivity of vaporization for water, Btu/ft^2
h_g	Mass transfer coefficient, $\text{lb}/\text{ft}^2\text{-hr}$
h_w	Inside heat transfer coefficient, $\text{Btu}/\text{ft}^2\text{-hr}^\circ\text{F}$
I	Percentage increase in evaporation
k_a	Equivalent conductivity, $\text{Btu}/\text{ft}^2\text{-hr}^\circ\text{F}$
$k_{g,0}$	Thermal conductivity of Humid air, $\text{Btu}/\text{ft}^2\text{-hr}^\circ\text{F}$

k_w	Thermal conductivity of water, $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
$k_{a/w}$	Thermal conductivity of air-water mixture, $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
L	Thickness of layer for convection heat transfer in dynamic solution, m
L_c	Distance between the water surface and glass cover, m
$n_{i,j}$	Mole fraction of species i near surface j
q_0	Stabilize output from control unit, $\text{Jou}/\text{m}^2\text{-day}$
q_1	Stabilize output from unit with dyn, $(\text{Jou})^2/\text{day}$
Q	Stabilize output, $\text{Jou}/\text{m}^2\text{-day}$
R_1	Molecular weight of molecular i , Jou/mole
n_1	Index of refraction for air-water vapor mixture
n_2	Index of refraction for dynamic solution
P_1	Partial pressure of water over surface 1, psia
P_c	Fractal factor
$q_{\text{sun}}(t)$	Solar radiation described in a layer, $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
q_a	Heat transfer by convection, Jou/hr
q_b	Spectral solar energy flux, $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
$q_b(t)$	Spectral solar radiation on a horizontal surface, $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
$q_{b,i}^+(t)$	Spectral solar radiation passing the air-water interface $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
$q_{b,i}^0(t)$	Spectral solar radiation incident on layer n , $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
$q_b(t)$	Incident solar radiation on glass cover, $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
$q(t)$	Total solar radiation on a horizontal surface, $\text{Jou}/\text{m}^2\text{-}^\circ\text{C}$
r	Reflections
R_{R}	Rayleigh number
S	Refracted gas constant, $\text{m}^3 \text{Jou}/\text{mole}^\circ\text{K}$
S	Slope of the regression lines in Figures 44 through 46
S_0	Schmidt Number

T_{sub}, T_0	Sublimation temperature, °C
T_{sub}, T_0	Temperature of hot and cold media, respectively, °C
T_0	Temperature of layer 0, °C
T_1, T_2	Temperature of the water surface and glass cover, respectively, °C
T_{air}	Ambient air temperature, °C
α_0	Thermal diffusivity of water, cm^2/s
α_1	Reflex absorptivity of glass
α_2	Absorption coefficient of the dye solution, lit/m^2
β	Thermal coefficient of volume expansion, $1/^\circ\text{C}$
δ_0	Thickness of layer, cm
$2a^2$	Half length of incident water molecules up to a layer, cm
$C_0(C)$	Dimensionless parameter in equation (20)
ϵ	Normalized absorption given by equation (14)
λ	Wavelength, nm
λ_1, λ_2	Short and long limits of wavelength of solar spectrum, nm
η	Efficiency of distillation
α_0	Kinematic viscosity of water, ft^2/s
$T_{\text{g/g}}$	Average transmission of transparent covered glass
λ_1, λ_2	Angle of incidence and reflection of atmospheric incident beams
μ	Density of fluid, lb/ft^3

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ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF
THE EFFECT OF SPIN ON SOLAR DISTILLATION

By

Ball Karna Rajwanshi

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Advisors: David A. Barker
Professor: D. R. Bales
Major Department: Mechanical Engineering

An analytical and experimental study of the effect of spin on solar distillation was conducted in this study. The analytical model developed treated the transient heat transfer inside the spin-water system as one dimensional. The bulk fluid was discretized into layers with convection, conduction and radiation interactions occurring between them. Coupled with this was the energy exchange from the surface of water in the glass cover by convection, radiation and evaporation of water. The bottom surface of the distiller was assumed to be insulated and a black absorbing. A FINTEC DIFFERENTIAL technique was used in solving the nonlinear partial differential equations. In the experiment section the chemical solar radiation, ambient temperature and the wind speed was used as input, the output from the program was the temperature-time history of the water layers and glass cover and the distiller output.

The experimental investigation was conducted using two identical water cells (2 ft. x 5 ft. x 4 ft.). The control cell contained water only while the other had dye-water solution. The dyes used were Black Naphthalene, Red Carmine and Fast Blue, with various concentrations. The Brown dye was made by mixing a 1:1 percent by-weight mixture of Naphthol Blue, Tartrazine and Red Carmine (all 500 ppm. powder). Test results showed that dye-water solution was able to increase the distillation output by as much as 25 percent (100 ft. with dye with 1000 ppm concentration). Based on these tests a simple method of calculating the percentage increase in evaporation afforded by a specific dye was given from the control cell was developed. The increase in output with the addition of dye was found to be proportional to the dye. However, no difference in the yield productivity, between the control and with dye, was noticed as a completely steady day. An important relationship was developed for evaporation heat transfer coefficient and the distillation output as a function of liquid surface temperature.

Among the dyes tested, Black Naphthalene dye was found to be most reliable from two points of view. Increased evaporation and lack of noticeable degradation by sunlight during periods of study. Red Carmine dye underwent severe degradation which resulted in the reduction of the absorption coefficient by as much as 85 percent at 0.5 cm wavelength after a month of exposure. The degradation of Brown dye was not as severe as the red dye, and this was primarily because of the red dye absorbed in it.

The results from the tests were compared with those from the experiment and the agreement between them was found to be excellent. The

effects of various concentrations, and subjecting the corn leaves to still previously was subsequently investigated. The model produced a decrease in output with increase in subject temperatures and no increase in still performance with wind speed.

An decrease in dimittion output resulted with increasing dye concentration, but became independent of concentration after 100 ppm. The change of increase of output with concentration of the dye was different for different dyes (among those tested) with black having the highest rate and Red having the lowest. A proposal was made of predicting an optimum dye concentration. The optimum concentration was defined as the concentration where the sum of the change of increase of dimittion with concentration when concentration and the dimittion with concentration was maximum. For the spring conditions at Gainesville, Florida, the optimum concentrations for Black, Green and Red dyes were 100 ppm, 125 ppm and 100 ppm, respectively. Recommendations for further research were given.

CHAPTER 1

INTRODUCTION

Water is the most abundant natural resource on earth. Essential to most human activities, it can mean life or death, health or poverty, war or peace. Abundant it is, but not infinite. Of the 410 million (41 million = 4.1×10^7) gallons of sea water that evaporates every year from the sea, only 26 million are available for possible use by life on earth. Of these 26 million only 20 percent can be utilized (1) which is about 10 million. At present the world uses 1.1 million. Thus, theoretically, we have enough supply of fresh water and the planned extension (2) predict that the hydrological cycle can support about 20 billion people with 70 percent utilization of the water resources. However, with the present rate of world population at 2 percent per annum, the available annual water supply will probably be insufficient for the world by the year 2000 A.D. Yet there is a basic flaw in the above reasoning when a major portion of the fresh water supply is not available where it is needed. This lacuna, in conjunction with the growth of population, will be the source of water shortage. Already quite a number of communities and nations do feel the pinch of water shortage because of this. However, the problem can be partially solved by transporting fresh water to areas of acute necessities, but the huge financial cost of such operations that have proved to be not feasible.

The problem is very well represented by the fact that in some of the arid and semiarid regions the ground water has high salt content or is contaminated and thus not fit for drinking. Even in areas well endowed with ground water supply, because of increased industrialization and population growth, the rate of depletion of these supplies is reaching alarming proportions. With the cost of water transportation already high, some other way of getting fresh water will have to be found.

One of the promising ways to solve this problem of water shortage appears to be desalination. Desalination processes already supply about 1.5×10^6 gallons of water per day (1960) in about a dozen countries [10]. Among the processes used about 85 percent are Multiple Effect Evaporation (MEE) type, due to the advanced stage of present-day technology in this area. The energy used in these plants is either petroleum or nuclear fuels. Thus, these plants are actually located in areas which are well endowed with fossil fuels. Indeed 90 percent of all the desalination plants in the world are located in Middle-East countries [14].

However, with increasing fossil fuel shortages and price rise, it is felt advised to look at some other methods of desalination which use renewable sources of energy like solar, wind and biomass among others. Interestingly enough, the areas which lack potable water supplies have abundant solar and wind energies, which is a strong case for using these renewable energy sources for desalination.

Solar distillation has been talked of a limited scale. Normally, the approaches have been used in using solar energy. One is the direct absorption of energy to reduce water and the other is indirect heating

of water and compressing it in a centralized facility. Only one big plant (capacity of 5,000 gpd in South America) has been built to date, using the second approach [1]. It is, nevertheless, in an experimental stage and when no evaluation has been given. However, it has been shown [6] that this second approach is consistently preferable for plants with capacity of less than 50,000 gpd. Thus the median superior the first approach, namely of direct absorption of reduction in saline water, is more suitable. This method is even more suited for small communities (about 200 people) in developing countries where an average of about 200 gpd of water is used for drinking and cooking purposes. In these communities setting up a large water desalination plant is economically unfeasible, both because of capital costs and transportation costs. Several research workers have therefore built, and experimented on, medium size water desalination units (ranged all from less than 10,000 gallons/day).

A solar stillification unit (water still) is a very simple device in operation but the heat and mass transfer in it is complex. Chapter III deals in detail with the energy transfer processes. Thus, in the present chapter it is sufficient to describe briefly the working of such a still which is schematically shown in Figure 1. Saline or brackish water is supplied continuously or intermittently to the pool. Working depth ranging from 1/3 inch to approximately 1 in 3 in. Depending upon the depth of water in basin a still is either called shallow basin (depth < 1 inch) or deep basin. The bottom of the basin is black to absorb solar energy and contains a drain to discard brine, continuously or periodically. Above the basin is a sloping



Figure 1. Schematic diagram of solar still

transparent cover of glass or plastic sheet, which acts as a condensing surface;

The incident solar radiation after passing through the glass cover is partially absorbed in the saline water, the major portion being directed to the basin bottom. Part is then transmitted down the basin surface into the water, thereby increasing its temperature. Partial vaporization of this heated water then occurs, and convection currents inside the still carry this warm vapor-laden air to the upper glass cover. Relative to change in the underside of this cover, the heat of condensation being retained through it to the surrounding atmosphere and the partially dehumidified air returns back to the surface of water for further addition of moisture. The thin condensation film flows down the inner side the following troughs and is collected in a distillate vessel. The output of these stills varies with various atmospheric conditions but on an average is between 10 to 25 gallons of fresh water per square foot of the basin area per year. Numerous variations of the above basic design have been experimented upon by thousands of others all over the world but the principle is the same. Some of these variations are described in the next chapter.

It will be seen, however, that even if these variations in design suffer from certain drawbacks which have made them technically and economically unattractive as distillation units. Then there is a need to design, build and analyze a better unit. With this in mind, the present work is an attempt to test the feasibility of a novel concept of using water soluble dyes to enhance solar energy absorption near the water surface, thereby increasing the productivity of the still.

CHAPTER II
LITERATURE REVIEW

Alcoholic Distillation

Alcohol distillation is not a new subject of study. It has been extensively studied for the past one hundred years [1, p. 112]. The first such study was conducted by an Italian, Nicolo Storti, in 1792, who proposed the following:

Perhaps placing a man here was considering not what he said a woman that the man's eyes will wander in good feeling with days and seasons, not an insignificant amount of tears will be formed and at the apex of that time he should have the man, he will remain in a state of tears and have a similar idea of death when.

But the earliest significant alcohol distillation plant we found was the one built by Charles Wilson in San Antonio, Texas, in 1870 [4]. The still was a shallow basin type, with a basin area of 48,000 ft² and was reported to have produced, when new, 1,500 U.S. gallons of fresh water daily for water working in the mining operation. Since then until the present day numerous such stills have been constructed and deployed both as a large scale (still do produce products about 1,500 gallons/day) and small scale (output of about 1 gallon/day).

An excellent summary of water distillation work done around the world from 1870 to 1970 has been presented by Valiente et al. [19].

the cover removed from the large distillation column of about 1-5 x 10³ gallons/ft² and the small laboratory scale models. The reported following operating and maintenance difficulties:

- a. Evaporation of seal in the heads for shallow heads stills, thus requiring frequent flashings and increased maintenance
- b. Leakage of the cover, especially the glass-to-cover, with what
- c. Leakage of brine from the heads and leakage of the vapor thereby reducing the productivity of the still

Besides the above, the major drawback of all these systems was the high LHV/LV ratio, which made them insensitive for other commercial uses.

In order to overcome the above problems several new designs of water distillation units have been experimentally investigated. However, these designs were based with previous knowledge making them unsuitable for large or even small scale usage. Thus, there is a need for a better distillation unit. But before such a unit can be proposed, it is necessary to look at some of the parameters affecting the productivity of water stills. In addition, such a study will also be useful in analyzing various designs built. The parameters affecting the performance of a still are:

1. Boiler radiation
2. Leakage of brine in the heads
3. Cover material and its shape
4. Ambient temperature
5. Wind velocity
6. Temperature of the condensing surface.

Soil Radiation

This is the most important atmospheric variable affecting the soil output. The amount of radiation absorbed by the basin is directly reflected in the productivity of soil. This absorption is governed by various factors, for example, depth of basin, the absorptive characteristics of water and walls of glass. These factors are explained below.

Basin Depth

The effect of basin depth on the output of solar stills is shown in Figure 2. The data in this plot are from a number of studies basin all over the world [4]. It can be readily seen that decreasing the basin depth increased the productivity. This was expected since the heat transfer to water in a shallow basin is very rapid, thereby increasing the surface temperature and hence the evaporation. Thus, most of the distillation output of shallow basin takes place during the day, whereas in the case of deep basin with an appreciable amount of water contained in the water and because of the thermal capacity of the still, the output is over a 24 hour cycle. In addition, the thermal losses from the sides and bottom of the deep basin still tend to be larger than those from a shallow basin still. Several studies, therefore, have been conducted on the shallow basin stills.

Researchers at the University of California have studied the cactus-type still [5]. The depth of the basin was about 1/4 inch. High output rates were obtained (2.15 gallons²/day or about 1000 Btu/hr² solar radiation input) but the still was heated with propane. This dry space in the basin, eliminating of black spray point, deposition of salts

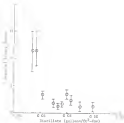


Figure 10. Effect of larval depth on adult productivity.

and high equipment expenses. Furthermore, for almost all the cost of you will run high. Earle Nelson [24] has studied extensively with type water stables. A person with stabled water like a milk can is covered by water water. Since the layer of the water is very thin (1/16 inch), there is rapid evaporation and loss of productivity because (output of 2 lb gal/ft²-day or about 2000 lb/ft²-day). However, there are severe problems of water clogging the pipes, dry spots developing resulting in deterioration of the milk material and greater amount of brine flow. These problems have resulted in making these stables non-attractive for commercial production. Recently the Corporation [25] produced a new type of milk material which is claimed to have self-cleaning properties so that it is not clogged by water. Since no detailed data are available, it is difficult to assess the potential as a commercial unit.

Several investigators have also looked at the effect of flowing water jets on the surface of snow so that the brine depth is effectively reduced. Suzuki (investigator [12]) reported an increase in productivity by 18 percent over the shallow stabled type stables, but the system was beset with problems of water accumulation and dry spots. Recently Saitoh [26] has reported results on reduction of brine layer with output of 0.467 gal/ft²-day. No results on self accumulation or dry spots were reported, however.

Excess Brine and Ice Stage

The water material has two functions. Besides allowing water radiation to pass through it, it acts as a conducting surface for water vapor. The first function requires that the water should transmit an

such reflection as possible and thus the water film on the outside should be thin. The second function requires that there should be least resistance in the transfer of heat of condensation meaning that the thickness of the cover material should be very small, there should be enough area of absorbing surface and the condensation should be dropless. However, it has been shown [11] that the decrease of solar radiation transmittance, because of formation of droplets on the outside of the glass, more than offsets the decrease in heat transfer. Thus film-type condensation rather than droplets is advantageous.

Normally, two types of cover materials are used: glass or plastic. The advantages of glass are high transmittance for solar radiation, high weatherability of glass and relatively high stability of properties over extended periods of time. The disadvantages are its relative poor strength and thus vulnerability to mechanical damage. This requires an increase in the thickness (usually 3/16 inch thick glass is used for covers). Plastic films normally used for solar stills have high solar transmittance (an average of 90 percent for 0.004 inch thick Teflon film at angles of incidence between 0 and 45 degrees, as compared to about 75 percent transmittance for 3/16 inch glass). In the area where these films have high infrared transmittance (80 percent in the wavelength region of 4 to 12 μ m) and high susceptibility to ultraviolet degradation. It is these properties, together with the fact that they have to be treated so as to make them water repellent, has made use of plastic cover construction in solar stills. Thus, until the advent of better plastic material which will overcome the difficulties listed above, it is believed that glass will be mostly used.

The slope of the cover is governed by three factors, namely a) it should provide enough condensing surface for water vapor, b) the angle should be such that it interrupts condensation only partially for the whole day, and c) the spacing between the cover and the water surface... The types of cover designed are usually made. One is the greenhouse type or double sloping cover (Figure 1) while the other has single sloping cover with the south facing side normally having a reflective surface as shown in Figure 2... However, it has been shown, both experimentally [14] and theoretically (cross shaped) that if enough condensing area is available then the effect of spacing between cover and water surface is negligible over the productivity. It also appears [17] that the effect of glass inclination on the amount of water condensation entering the still is small, because the insolation over the slope horizontal though is the same as tilted with... Thus the major factor governing the slope of the cover is the availability of enough condensing area. It is interesting to note that very few investigators appear to have considered this factor in design of their stills... Most have tried to minimize the spacing between the cover and the water surface which ultimately results in less insolation in the absence of enough condensing surface.

Airflow Temperature and Wind Velocity

These two variables have been lumped together because they affect the productivity of the still by their effect on the temperature of the cover. As the ambient temperature increases the amount of heat transfer from the cover to the atmosphere is reduced, thus decreasing the productivity. However, some computer results of Lal et al. [24],

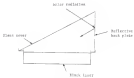


Figure 2 Single sloping solar still

Ross [19] and Hirsman et al. [20] have shown that there is an increase in output of the still with increasing relative humidity. These results are not backed out by actual experiments [14].

Because of wind velocity increases the relative heat transfer coefficient thereby decreasing the heat loss from the water and the productivity. However, Lal et al. [14], Ross [19] and Hirsman et al. [20] have published their increases of wind velocity decreases the output. They found that as increase of saturated heat transfer coefficient from 1.5 to 20 Btu/ft²h^{0.75} decreased the output by 25 percent. Again, this is not backed out by experiments [21], calculations [19] and by computer analysis (present work).

Importance of the condensing surface

The temperature of the condensing surface is a function of both the brine temperature and the ambient conditions. A greater difference between the brine and ambient temperature results in increase of the productivity of the still. However, during the daytime, because of higher brine temperature this difference is not maximum. Several investigations have tried to increase this difference by providing an external condenser for water vapor. Gross et al. [22] constructed a condenser tower on blowing air through the still and condensing the water vapor in an external water-cooled condenser. Buckle [23] developed a multiple effect water still where the heat of condensation from the first effect is used to provide the heat of evaporation at the second effect and so on. The statement of the heat effect was backed by water. Datta and Bhatia [24] used two inflated plastic tubes with the lower tube partially filled with cold water over which the

and two levels. Other water vapor levels are not shown since no air entered, indicating where the water was condensed. The reported still efficiencies (efficiency = $\frac{\text{energy used in evaporating water}}{\text{total solar energy input to the still}}$) were between 10 and 40 percent on bright summer days. Besides low efficiencies this system suffered from another drawback, the deterioration of the plastic tubes--

although production as high as 5.21 gal/hr²-day on a bright summer day was reported by Evans et al. [13], the additional costs required in expenses for air heating and water circulation were more about the same as yield. Further conclusions were also reached by Smith [20], who also reported the problems of corrosion of the metal condenser by saline water. There are other factors also which affect the output of solar stills-- They are land still construction as in to have uniform water tightness, as in minimal leakage of brine from the heating panel, insulation of the sides and bottom for shallow basin stills; and the frequency of flushing and the orientation of the still [19].

From the above considerations of various parameters affecting a solar still, some of the desirable features of a good distillation unit are:

- a. To ensure maximum absorption of solar radiation near the surface of brine--
- b. Good condensing cover temperature
- c. Minimum amount of maintenance and flushing

In the present study a design of a still has been investigated which incorporates the above features-- By using water column data in the saline water, solar radiation can be absorbed in a thin (1" depth)

surface layer of brine. At the same time as the brine is made deep, then the well will also work during night-time, thus using the advantage of major consumer surface. The problem of well building (and thus periodic flooding) is also reduced because it enables of the bottom of the basin and thus not interfere in the water collection operation near the surface.

Use of Dye to Estimate Well Permeability

The use of water soluble dye to measure permeability of soil is not a new concept. Back in 41 [17] were the first to study the effect of triphenyl brown dye on the permeability of brine for deep aqua salt production. They tested this dye in different depth points and for different concentrations. It was found that if enough dye was added (10 g/g by weight) the depth of the point does not have too much effect on permeability (the difference in permeability was less than 5 percent for brine layers of 30 cm and 50 cm deep). They also report that with the same concentration of the dye the increase in permeability of 10 percent over that of uncolored brine was obtained. However, in attempt was made to study the effect of other dyes, the effect of porosity on the degradation of the dye as to correlate their experiments with analytical results. The use of dye for salt production subsequently became an accepted practice. However, very little data are available on the permeability that affect production below level of 50. Information is proprietary in nature [18].

Major cases of coloring the brine have been tested with United States. The use of red isopropyl alcohol-soluble in blue green dyes

system has been used to enhance the separation of latex [24]. The advantages of such a system are obvious. There is no color degradation of the bacteria and at the same time the culture can be obtained free from the water which is added to culture, thus avoiding the use of costly dye analogues, which are not easy to remove. However, these bacteria are extremely susceptible to changes of pH, temperature, and impurities and have not been identified commercially successful [25].

Byers et al. [26] have extended Black's work to include other dye and tested their degradation by sunlight. Among the six dyes tested Diphenyl Green was the most stable in the presence of latex emulsion and sunlight for the test period of 4 weeks. However, conflicting reports were published on the effect of some of these dyes on color degradation. It was reported that Black Euphrasia and Congo red dye do not increase the separation of latex, while Diphenyl Green increases it by 7 percent as opposed to 15 percent increase achieved by Black et al. [27].

Byers et al. [26] developed an analytical model of the system. However, the model failed to take into account the optical and color characteristics of suspensions of the latex.

From the brief description of the effect of dye on color separation it is evident that hardly data are available on their use with an assay done on their use for color discrimination. Further this lack of experimental data no detailed analysis has been conducted on the effect of dye on color separation and on optical and temporal variations of the detection system. The present work is directed as an attempt to study some of these effects.

Scope of the Present Investigation

The present investigation is an attempt to achieve the following objectives:

1. To develop a simple analytical model for study of the effect of different parameters on predictability of solar stills. These parameters are ambient temperature, wind velocity, type of dye and concentration. The model will be developed for prediction of temperature-time history of the dye-water system and the glass cover for different environmental conditions and local solar radiation. The model is developed in Chapter III.
2. To experimentally evaluate the effect of different dyes on predictability of single basin solar still. The predictability from this still is compared with that from an identical control still. Chapter IV presents the experimental setup and procedure.
3. To discuss experimentally the absorption spectrum of the dyes used in this study. The dyes used are Erythrosine (Red), Eriochrome (Red) and mixture of Erythrosine Blue, Carmoisine and Eriochrome (Red-Green).
4. To compare the results obtained from this experiment with that from the analytical model. This comparison is presented in Chapter V.

CHAPTER IV THEORETICAL ANALYSIS

In this chapter a theoretical analysis for a deep brack distillation unit is presented.

Figural Model

Figure 4 is a sketch of a deep brack distillation unit¹ in which the energy extraction of a vap from the sea as it passes through the condenser cooled glass and into the evaporator chamber². In order to analyze the energy transfer process in the brack the evaporator system has been divided into discrete layers of thickness Δz . An energy balance is then given for these layers often making the following assumptions:

- i) The dimensions of each layer, as shown in Figure 4, is the y - z dimension are large compared to those in the x direction and $\Delta x \ll L^2$, so that the temperature varies only in the x direction.
- ii) In the temperature-range normally encountered in the brack distillation units, the changes in physical properties of the

¹Flow number (B.P.) is defined later as the cost

(possibly large refractive index, possibly small gap distance) conductivity are negligible

3. The material selection and mounting coefficient of the dynamic resistance is assumed to be small and often negligible;
4. The transmission of the incoming solar radiation by the glass with continuous film inside has been taken into account by averaging out the reflection and absorption losses with respect to angle of incidence;
5. The inner surface of the wall is assumed to be a black absorber;
6. There is negligible contribution of solar radiation as it passes through the air-water vapor mixture inside the wall.

With the above assumptions, the energy balance at the n^{th} layer or distance z_n then leads to the following

$$\left[\begin{array}{c} \text{Rate of increase of} \\ \text{energy stored} \end{array} \right] = \left[\text{Rate of energy in} \right] - \left[\text{Rate of energy out} \right] \quad (1)$$

where energy in is the n^{th} layer receipt of,

$$\left[\begin{array}{c} \text{Rate of energy} \\ \text{in} \end{array} \right] = \left[\begin{array}{c} \text{Rate of solar radiation} \\ \text{absorbed in } n^{th} \text{ layer} \end{array} \right] + \left[\begin{array}{c} \text{Rate of energy in} \\ \text{by convection from} \\ \text{layer } n+1 \end{array} \right] + \left[\begin{array}{c} \text{Rate of energy in by} \\ \text{conduction from layer} \\ \text{ } n+1 \text{ or } n+2 \end{array} \right] \quad (2a)$$

and rate of energy out can similarly be written as:

$$\begin{aligned}
 \left[\begin{array}{c} \text{Rate of energy} \\ \text{out} \end{array} \right] &= \left[\begin{array}{c} \text{Rate of energy out by conduction to} \\ \text{input oil at } u+1 \end{array} \right] \\
 &+ \left[\begin{array}{c} \text{Rate of energy out by} \\ \text{convection in layer} \\ u+1 \end{array} \right] + \left[\begin{array}{c} \text{Rate of energy out by conduction} \\ \text{from the sides to environment} \end{array} \right]
 \end{aligned}
 \quad (3)$$

At the upper boundary (assuming insulated the energy is losses derived to the glass cover by convection, radiation and conduction)

Thus, the instantaneous energy balance on the surface leads to:

$$G = [\text{Rate of energy in}] + [\text{Rate of energy out}] \quad (3a)$$

where

$$\begin{aligned}
 [\text{Rate of energy in}] &= \left[\begin{array}{c} \text{Rate of energy in by conduction} \\ \text{from input 1} \end{array} \right] \\
 &+ [\text{Rate of energy in by conduction from input 2}]
 \end{aligned}
 \quad (3b)$$

and

$$\begin{aligned}
 [\text{Rate of energy out}] &= \left[\begin{array}{c} \text{Rate of convection of water} \\ \text{from the surface} \end{array} \right] \\
 &+ [\text{Rate of radiation loss to the glass cover}] \\
 &+ [\text{Rate of conduction loss to the glass cover}]
 \end{aligned}
 \quad (3c)$$

At the lower boundary, namely the tank (Figure 1d), the energy balance is:

$$[\text{Rate of energy in}] = [\text{Water radiation absorbed in this layer}] \quad (3d)$$

and

$$\begin{aligned}
 [\text{Rate of energy in}] &= \left[\begin{array}{l} \text{Rate of energy incident upon the} \\ \text{on b-i layer} \end{array} \right] \\
 &+ [\text{Rate of energy loss by conduction to base}] \\
 &+ [\text{Rate of energy loss by conduction in layer b-i}] \\
 &+ [\text{Rate of energy loss by conduction from the sides}] \quad (2a)
 \end{aligned}$$

Further, the energy balance on the glass cover plate

$$\begin{aligned}
 [\text{Rate of energy in}] &= [\text{Solar radiation absorbed by glass cover}] \\
 &+ \left[\begin{array}{l} \text{Rate of energy in by convection from the dynamic} \\ \text{surface} \end{array} \right] \\
 &+ \left[\begin{array}{l} \text{Rate of energy in by radiation from the dynamic} \\ \text{surface} \end{array} \right] \\
 &+ \left[\begin{array}{l} \text{Rate of energy in by convection from dynamic} \\ \text{surface} \end{array} \right] \quad (2b)
 \end{aligned}$$

$$[\text{Rate of energy out}] = \left[\begin{array}{l} \text{Rate of energy loss by convection} \\ \text{and radiation to the environment} \end{array} \right] \quad (2c)$$

Therefore,

$$\left[\begin{array}{l} \text{Rate of} \\ \text{energy in} \end{array} \right] = \left[\begin{array}{l} \text{Rate of} \\ \text{energy out} \end{array} \right] + \left[\begin{array}{l} \text{Rate of increase of energy} \\ \text{stored in the glass cover} \end{array} \right] \quad (2d)$$

Incident Solar Radiation

The incoming spectral solar radiation reaching the absorber surface is considered to having wavelength in the range of 0.2 μ m to 3.0 μ m. The choice of this range has been dictated by the fact that most of the radiation after 3.0 μ m is absorbed by the condenser film on the glass surface. Furthermore, to facilitate computation, the solar spectrum [11] has been described by fitting a polynomial in the above range. The radiant flux then can be written as

$$q_{\lambda} \left(\frac{\text{cal}}{\text{cm}^2 \text{ sec}} \right) = \begin{cases} 43794 + 11.5 \lambda, & 0.2 \mu\text{m} \leq \lambda \leq 0.5 \mu\text{m} \\ 1181.3 \exp(-1.846\lambda), & 0.5 \mu\text{m} \leq \lambda \leq 3.0 \mu\text{m} \end{cases} \quad (2)$$

The spectrum given by equation (2) is the maximum radiation available at the solar noon on a clear day, and thus will have to be modified for different hours of the day. This modification is achieved by assuming that the "shape" of q_{λ} remains the same but the peak value, the value of q_{λ} at λ becomes equal to the total solar radiation falling on a horizontal surface at time t during the day.

If the solar radiation incident on a horizontal surface at time t is given by $q(t)$ then $q_{\lambda}(t)$ becomes:

$$q_{\lambda}(t) = q(t) \cdot q_{\lambda} \quad (3)$$

where

$$q(t) = \frac{-dQ(t)}{dt} = \int_{0.2}^{3.0} q_{\lambda}(t) d\lambda \quad (4)$$

Attenuation of Reflection

The incident angle of water reflection on the dyewater surface changes with time, as shown in Figure 2. This change in the angle of incidence changes the absorption coefficient for any layer of thickness dx

Thus, from Snell's law,

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_2}{n_1} \quad (11)$$

where n_1 = index of refraction for air-water vapor mixture and n_2 = index of refraction for water-dye mixture.

Since the speed of water waves, as compared to the air inside the HULL, is small, it is assumed that $n_2 \gg 1$. Also it has been assumed that the index of refraction for dyewater mixture is the same as that for pure water and both n_1 and n_2 remain constant for the range of wave-lengths from 0.3 μ m to 3 μ m.

From Fresnel equations the reflectance can be calculated by knowing n_1 and n_2 and is given as:

$$r = \frac{1}{2} \left[\frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)} \right] \left[1 + \frac{\cos^2(\theta_i - \theta_r)}{\cos^2(\theta_i + \theta_r)} \right] \quad (12)$$

and for $\theta_i = \theta_r$,

$$r = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 \quad (12a)$$

Thus, the amount of solar radiation passing through the water-air interface has to be multiplied by the transmittance of both the water-air interface and condensation covered glass. For the condensation covered glass an average transmittance value $\bar{\tau}_{gwa}$ has been obtained from experimental data. Therefore, the radiation passing the water-air interface is...

$$\dot{q}_{s_{w-a}}^{\text{net}}(t) = \bar{\tau}_{gwa}(t) \cdot c \cdot q_s^{\text{net}}(t) \quad (136)$$

where $q_s^{\text{net}}(t)$ is obtained from equation (9), and c is given by equations (10) and (11) above.

The path length of the incident radiation is:

$$ds^{\text{net}} = ds^{\text{net}} \sin \theta_i \quad (14)$$

where ds^{net} is the path length of the ray of incident solar radiation for a layer of thickness ds . As can be seen from equation (14), ds^{net} is also a function of time.

The absorption of incident radiation in the dry-water medium takes place in accordance with the Beer's law [21]. Thus, the amount of energy absorbed in a layer of thickness ds^{net} is

$$\dot{q}_{s_{w-a}}^{\text{abs}}(t) = \left(\frac{1}{\lambda_1} \right) \cdot \dot{q}_{s_{w-a}}^{\text{net}}(t) \cdot d\lambda = \left(\frac{1}{\lambda_1} \right) \cdot \dot{q}_{s_{w-a}}^{\text{net}}(t) [\cos \theta_i - \alpha_1 ds^{\text{net}}] d\lambda \quad (15)$$

where $\dot{q}_{s_{w-a}}^{\text{net}}(t)$ is the incident spectral radiation on the layer n and α_1 is the spectral absorption coefficient of the medium. The absorption coefficients of different dry have been obtained experimentally and will be discussed in greater detail in Chapter 5.

Conduction and Convection Heat Transfer in Ice-Water System

The heat transfer in a layer of thickness L occurs by both conduction and convection from adjacent layers besides the radiative reflection observed by us. The conduction heat transfer is mainly useful while for convection the concept of equivalent conductivity [26] is used. Thus, the average heat flow per unit time because of convection is characterized by equivalent conductivity k_e defined as

$$q_{\text{conv}} = \frac{k_e}{L} (T_H - T_C) \quad (14)$$

where L = thickness of layer

T_H, T_C = temperatures of hot and cold layers, respectively.

The data for equivalent conductivity for given layers from different investigations has been plotted [26] and fall on a straight line, given by

$$\ln k_e \left[\frac{L}{k_w} \right] \begin{cases} = 0.1 \ln_{10} B_{12} - 4, & \text{for } B_{12} > 10 \times 10^4 \\ = 0.15 \ln_{10} B_{12} - 9.7, & B_{12} \leq 10 \times 10^4 \end{cases} \quad (15)$$

where k_w = conductivity of the water

B_{12} = Biot-like factor based on thickness L of the layer

$$= \frac{k_w (T_H - T_C) L^3}{q_{\text{conv}} \alpha_w}$$

β = thermal expansion coefficient of water

η = viscosity due to gravity

α_w = kinematic viscosity of water

α_w = thermal diffusivity of water

heat loss from the sides of the layer to the environment is¹

$$q_{\text{loss, sides}} = \lambda a(T_m - T_a) \quad (18a)$$

where T_a and T_m are temperatures of layer a and the environment, respectively. The lower half is the product of overall heat transfer coefficient U between the water-side surface and the environment, and the perimeter P of the vial. Equation (18) is a one-dimensional model, as implied that film resistances $\{R_f\}$ be much less than 1, where R_f is

$$R_f = \frac{h_a}{k_a} \quad (18b)$$

where k_a is the heat of the layer. The value of R_f for the present case is 0.25. This makes the one-dimensional assumption reasonable.

Evaporation and Condensation from the Water Surface

The heat transfer inside the vial occurs mainly by diffusion and convection of the air-water mixture. Bock and Strauss (20) have done laser-Doppler studies on a laboratory vial and found that most of the energy transfer by evaporation of water and condensation from the water surface takes place in a boundary layer which circulates inside the vial. The bulk of air in the center of the vial remains essentially stationary. Thus, the evaporation rate is determined by the energy balance heat and mass transfer for this situation.

The heat transfer by convection from the water surface to the glass cover is given by²

$$q_a = U_a A_a (T_a - T_g) \quad (19)$$

where h_g is the heat transfer coefficient and t_g is the average glass pane thickness. There is spatial temperature variation in the glass cover because of the geometry of the still but for the sake of simplicity an average temperature between the top and bottom portion of the glass has been used.

The heat transfer coefficient h_g can be calculated from the following semi-empirical equation [36]:

$$h_g = 0.026 Re^{1/4} Pr^{1/4} \quad (28)$$

where Re = Reynolds number = $\frac{\rho_a u_a l}{\mu_a}$

Gr = Grashoff number = $\frac{g \beta_a (T_{in} - T_{out}) l^3}{\nu_a^2}$

and Pr = Prandtl number = $\frac{\mu_a c_p}{k_a}$

β = Coefficient

The choice of exponent p and constant C in equation (28) is dictated by the Grashoff number. In the temperature ranges encountered in the solar still the exponent p has the value of 1/4. It should be noted that h_g from equation (28) is independent of length l [distance between the water surface and the glass cover for most stills]. Experimentally the above fact is not true and because there is heat and mass coupling on the glass cover on the other side, which changes the free convection pattern.

The frequency factor (h_g/ρ) in the Grashoff number of equation (28) was estimated for the conditions of constant composition of the evaporating fluid. However, this has to be modified for the solar still

where ρ_{mix} is the density of air-steam along the pipe.

This modification is achieved by assuming that air-steam vapor mixture is an ideal gas [18].

Thus,

$$\rho_{\text{mix}} = \rho_v + \rho_a = \frac{P_v M_v}{R T} + \frac{P_{\text{air}} M_{\text{air}}}{R T} \quad (26)$$

where ρ_{mix} = density of water-air mixture

P_v = partial pressure of water vapor

P_{air} = partial pressure of air

and M_v, M_{air} = molecular weights of water and air, respectively

R = universal gas constant

T = temperature of the steam

For an enclosed space,

$$P_v + P_{\text{air}} = P_{\text{total}} \quad (27)$$

In the case of a water still, when its is open to the atmosphere

$P_{\text{total}} = P_{\text{atm}}$. Therefore, equation (26) is modified as

$$\rho_{\text{mix}} = \frac{P_v M_v}{R T} + \frac{(P_{\text{atm}} - P_v) M_{\text{air}}}{R T}$$

Thus, the density of water-air mixture near the glass cover and on the water surface can be respectively written as

$$\rho_{\text{mix}}|_R = \frac{P_{\text{vR}} M_v}{R T_R} + \frac{(P_{\text{atm}} - P_{\text{vR}}) M_{\text{air}}}{R T_R} \quad (28)$$

and

$$P_{\text{avg}}|_a = \frac{P_{\text{avg}}|_b}{1 + \frac{R}{R_0}} + \frac{(P_{\text{avg}} - P_{\text{avg}}|_b) R_0 R}{R + R_0} \quad (19)$$

where

$$R = P_{\text{avg}}|_b - P_{\text{avg}}|_a$$

and $P_{\text{avg}}|_b$ is the arithmetic mean of $P_{\text{avg}}|_a$ and $P_{\text{avg}}|_a^{(0)}$

After algebraic manipulation

$$\frac{R}{R_0} = T \frac{dI_{\text{avg}}}{dV_{\text{avg}}} \quad (20)$$

where

$$R = \frac{P_{\text{avg}}}{I_{\text{avg}}} \left[\frac{P_{\text{avg}} + (P_{\text{avg}} - P_{\text{avg}}|_b) \frac{R_0}{R_0 + R}}{P_{\text{avg}} + (P_{\text{avg}} - P_{\text{avg}}|_b) \frac{R_0}{R_0 + R}} \right]$$

and R_0 from equation (16) then becomes

$$R_0 = C R_{\text{avg}} \left(\frac{dI_{\text{avg}}}{dV_{\text{avg}}} \right) \left(\frac{V_{\text{avg}}}{R_{\text{avg}}} \right)^{1/2} \quad (21)$$

The non-linear coefficient is defined as

$$J = R_{\text{avg}}(a_{1a} - a_{1a}') \quad (22)$$

where,

J = non-linear ratio per unit area

R_{avg} = non-linear coefficient, $\text{mhos}/\text{area} = \text{ohm}$

$(a_{1a} - a_{1a}')$ = driving potential for the non-linear, dissymmetric

$$A = \sum_{j=1}^N \left(\frac{1}{\omega_j} \right) \text{ mass (frequency at position } j) \text{ where subscript } j \text{ implies near the surface and } n_s \text{ is the eigenspectrum}$$

From analogy between heat and mass transfer, an equation similar to equation (100) can be written for mass transfer. Then,

$$B_{0m} = 1 - (B_{0m} / B_L)^2 \quad (101)$$

where

B_{0m} = Graetz's number for mass transfer

B_{0m} = mass transfer Biot's number = $\frac{h_p h}{k B_{Lj}}$

p = average density of the mixture

h_{Lj} = Henry's diffusion coefficient in mass diffusivity

B_L = Schmidt number = $\frac{\nu_{Lm}}{D_{Lj}}$

ν_{Lm} = kinematic viscosity of the mixture

†

The above analogy is based on the following assumptions:

- (a) Small rate of mass transfer
- (b) No chemical reactions in the fluid
- (c) Negligible viscous dissipation
- (d) Negligible emission or absorption of radiant energy

In a solar still there is combined heat and mass transfer from the surface of water. For each n there the ratio of B_{0h} and B_{0m} proves to be function of Pr , Sc , and the ratio of viscosity defined by the temperature difference is then defined by the mass concentration ratio. This latter ratio is 1 if Pr is Sc , which refers to the case

for water evaporating in air. Thus the problem is simplified in the sense that mass and heat transfer can be treated separately. Hence,

$$h_{01} = C \text{ Gr and } \lambda^2/2 \quad (10)$$

and h_{01} is given as:

$$h_{01} = C h_{11} \exp\left(\frac{C(h_{11}h_{21})\lambda^2/2}{h_{01}h_{11}}\right) \quad (11)$$

and heat exchange because of mass transfer is:

$$q_{01} = h_{01} h'_{11} (a_{11} - a_{01}) h_{21} \quad (12)$$

where h_{21} = mass transfer coefficient

λ = size of the shell

$(a_{11} - a_{01})$ = mass transfer driving potential

h'_{11} = coefficient of vaporization

Thus, from equations (11) and (12) the mass fraction of species in:

$$w_{01} = \frac{C_{01}}{\rho} = \left(\frac{C_{01} h_{11}}{\rho} \right) \exp\left(\frac{C_{01} h_{11}}{\rho} \right) + \frac{(C_{01} a_{01} - C_{01} a_{01})}{\rho} w_{01}$$

or,

$$w_{01} = \frac{C_{01} h_{11}}{C_{01} h_{11} + (C_{01} a_{01} - C_{01} a_{01}) w_{01}} \quad (13)$$

Similarly,

$$w_{11} = \frac{C_{11} h_{11}}{C_{11} h_{11} + (C_{11} a_{11} - C_{11} a_{11}) w_{11}} \quad (14)$$

Examination of functions

The difference equations have been written for different sections and have been then identified

Top layer

Combination of equations (3) and (2) gives

$$\begin{aligned} k \left(\frac{1}{\lambda_1} \right) \psi_{k+1}^T(1) \psi_k^T(0) &= \left(\frac{1}{\lambda_1} \right) \psi_{k+1}^T(0) \left(\exp(-\alpha_1 \lambda_1^2) + \alpha_1 \right) + \frac{k_1 \lambda_1}{\lambda_1} (\psi_{k+1}^T - \psi_{k+1}^T) \\ &+ \frac{k_1 \lambda_1}{\lambda_1} (\psi_{k+1}^T - \psi_k^T) = (\psi_{k+1}^T - \psi_k^T) \text{ or } \alpha_1 = \alpha_1 + \alpha_1 \lambda_1 \left(\frac{\psi_{k+1}^T - \psi_k^T}{\lambda_1} \right) \quad (9) \end{aligned}$$

where

k_1 = apparent conductivity given by equation (15)

λ_1 = area of the layer

In the above equation if there is no convection then k_1 simply becomes equal to k . The boundary conditions can be written as

Top layer

Combining equations (3) and (4) give the temperature of the top layer. Thus,

$$k_1 \lambda_1 \frac{(\psi_{k+1}^T - \psi_k^T)}{(\Delta x/\lambda_1)} = k_1 \alpha_1 \lambda_1 + \alpha_1 \lambda_1^2 \psi_{k+1}^T + \alpha_1 \lambda_1^2 \psi_k^T + \alpha_1 \lambda_1^2 \lambda_1 (\psi_{k+1}^T - \psi_k^T) \quad (10)$$

where

λ_1 = conductivity along direction between water surface and plane
area

$\Gamma_{\pm}$ = geometrical shape factor between water surface and glass cover

Bottom Surface

An instantaneous energy balance on bottom surface yields

$$\begin{aligned} & \Delta t \left(\int_{\Delta} \frac{\partial}{\partial t} \rho_{\text{water}}^2 dV \right) (\text{net-} q_{\text{net}} \Delta t) \Delta t + \\ & \frac{h_{\text{gl}} \text{net} q_{\text{net}}^2 + (T_{\text{gl}}^2 - T_{\text{ext}}^2)}{\Delta t_{\text{gl}}} + \frac{h_{\text{ext}} \text{net} q_{\text{net}}^2 + (T_{\text{ext}}^2 - T_{\text{ext}}^2)}{\Delta t_{\text{ext}}} \end{aligned} \quad (20)$$

where

$\rho_{\text{water}}^2 dV$ = the total energy incident on the water-side interface

Δt = transmission length for the water system

as shown in Figure 4

h_{gl} = conductivity of Plexiglas

Δt_{gl} = thickness of the Plexiglas

h_{ext} = conductivity of the Plexiglas bottom

Substituting equation (20) in the assumption that the bottom surface is a black absorber so that all the energy incident on it is absorbed.

Energy Balance with the Balla Group

The right-hand side of equation (11) gives the rate of energy loss from the glass and aluminum cover. This energy must be given up to the environment. At the same time there is a small amount of solar radiation absorbed by the glass cover. Thus, the temperature of the cover can be obtained from the following equation:

$$\begin{aligned}
& \sigma_{\text{eff}}^{\text{eff}} \left(1 - \frac{1}{\epsilon_{\text{eff}}} \right) \left(\frac{1}{\epsilon_{\text{eff}}} \right) + \epsilon_{\text{eff}} \epsilon_{\text{eff}} \epsilon_{\text{eff}} + \epsilon_{\text{eff}} \epsilon_{\text{eff}} + \epsilon_{\text{eff}} \epsilon_{\text{eff}} + \epsilon_{\text{eff}} \epsilon_{\text{eff}} + \epsilon_{\text{eff}} \epsilon_{\text{eff}} \\
& + \epsilon_{\text{eff}} \epsilon_{\text{eff}} \left(\frac{1}{\epsilon_{\text{eff}}} - \frac{1}{\epsilon_{\text{eff}}} \right) + \sigma_{\text{eff}}^{\text{eff}} \epsilon_{\text{eff}} \left(\frac{1}{\epsilon_{\text{eff}}} - \frac{1}{\epsilon_{\text{eff}}} \right) + \epsilon_{\text{eff}} \epsilon_{\text{eff}} \epsilon_{\text{eff}} \frac{d\epsilon_{\text{eff}}^{\text{eff}}}{dt} \\
& + \epsilon_{\text{eff}} \epsilon_{\text{eff}} \epsilon_{\text{eff}} \frac{d\epsilon_{\text{eff}}^{\text{eff}}}{dt} \left(\frac{1}{\epsilon_{\text{eff}}} - \frac{1}{\epsilon_{\text{eff}}} \right)
\end{aligned} \quad (33)$$

where

$\epsilon_{\text{eff}} = \text{area of millimeter} = \epsilon_{\text{eff}} + \epsilon_{\text{eff}}$

$\epsilon_{\text{eff}} = \text{glass cover area}$

$\epsilon_{\text{eff}} = \text{aluminum back plate area}$

$\epsilon_{\text{eff}} = \text{total absorptivity of glass}$

$\epsilon_{\text{eff}} = \text{surface construction heat transfer coefficient}$

$\left(\frac{1}{\epsilon_{\text{eff}}} \right) \epsilon_{\text{eff}} = \text{density of glass and aluminum, respectively}$

$\epsilon_{\text{eff}} = \epsilon_{\text{eff}} = \text{specific heat of glass and aluminum cover, respectively}$

$\epsilon_{\text{eff}} = \epsilon_{\text{eff}} = \text{thickness of glass and aluminum cover, respectively}$

$\epsilon_{\text{eff}} = \text{effective surface absorptance for radiation}$
 $= \epsilon_{\text{eff}} = 1/2 \quad (34)$

and other symbols are defined before.

Experimentally it was found that during daytime the temperature of the aluminum back plate was greater than the surface temperature of water. Thus, no convection took place on the back plate. At night, however, there was convection on the aluminum plate but the convection was equal to that of the glass cover. However, an order of magnitude analysis of equation (33) shows that the storage term in

the condition is negligible, that all the calculations $\text{for } \frac{\partial \psi}{\partial t}$ in the above equation can be considered as $\bar{\psi}_B$. This yields

Finite Difference

$$\begin{aligned} \text{or } \rho_A \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) + \rho_B A \left(\alpha_{12} - \alpha_{22} \right) \bar{\psi}_{12} + \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) + \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) \psi(t) \\ + \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) = \text{or } \rho_B \rho_{AB} \bar{\psi}_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) + \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) \bar{\psi}_B \frac{\partial \bar{\psi}_B^{\text{old}}}{\partial t} - \bar{\psi}_B^k \end{aligned} \quad (14)$$

Finite Difference

$$\begin{aligned} \text{or } \rho_A \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) + \rho_B A \left(\alpha_{12} - \alpha_{22} \right) \bar{\psi}_{12} + \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) + \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) \psi(t) \\ + \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) = \text{or } \rho_B \rho_{AB} \bar{\psi}_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) + \rho_B \left(\bar{\psi}_B^k - \bar{\psi}_B^{k-1} \right) \bar{\psi}_B \frac{\partial \bar{\psi}_B^{\text{old}}}{\partial t} - \bar{\psi}_B^k \end{aligned} \quad (15)$$

Note the change in cover state for top and right in the above equations.

Method of solution

The depth of the well is 10.5 inches and with grid size of $\Delta x = 1$ inch there are 11 nodal equations and two boundary conditions for the top and bottom channels. Therefore, a computer program was written to solve these 11 nodal equations for the dynamics, and one equation for the glass cover, simultaneously. Explicit method of solution was used in solving them and therefore the time interval Δt was carefully chosen so as to avoid unstable solutions. Appendix III shows the stability

relation used in the previous analysis; below are listed the steps used in getting the temperature-time history of various layers

1. The temperatures of the layers and glass cover are calculated at various times using their experimental values. Thus, T_g^1 and T_g^2 are known. This used in the program to the actual solar insolation, ambient temperature and wind velocity
2. Since T_g^1 and T_g^2 are known then equation (10) is solved to obtain T_g^3 . The solution of equation (10) is by regula-falsi method (14)
3. Equations (14), (16) and (18) or (19) are then solved for $T_g^{1+1\Delta t}$ and $T_g^{2+1\Delta t}$
4. Once the temperature vs depth profile is generated from step 3, then the apparent emissivity ϵ_a is calculated. The method of calculation is as follows:
 - (a) Calculation of $T_{a,max}$, as shown in Figure 4
 - (b) All the layers above layer 1 will have same surface temperature with $\Delta T = T_{a,max} - T_a$ and emissivity ϵ_a is calculated using equation (2) and depth z
 - (c) The layers below the n^{th} layer have heat transfer between them by conduction only
5. Steps 3 or 4 are then repeated with an increment of time Δt , till a 24 hour cycle is completed

Figure 7 shows the detailed flow diagram of the computer program used to generate temperature-time history for different layers

The results of the analytical model are presented in Chapter 8.



Figure 4. Temperature profile of the lap joint.



Figure 2 Flow diagram of the computer program

CHAPTER IV

EXPERIMENTAL SETUP AND PROCEDURES

Flaskholder Design

Two identical duty bottles under distillation setup were constructed (see Figure 3). One of these was used as a control while the other was used for testing the effects of α -pin. The bottles of these stills are made of 3/8 inch thick stainless which was selected for its strength and corrosion resistance to acid vapors. Figures 4 and 5 show the sides of the stills. Flangeless plates were bolted together and were glued using epoxy resin to make them water tight. Before experiments the bottles were tested for water tightness. The overall dimensions of each bottle were 4 ft. x 4 ft. x 1 ft. These bottles were joined on the inside using two rows of stainless-steel blank pins which acted as a blank liner for the stills. At the top of the bottle, extended circular angle of dimensions 2 inches x 1-1/4 inches and 1/16 inch thick was bolted in order to support for the glass cover frame.

The glass cover frame was made of stainless steel pipes, shown schematically in Figure 3b. Its size was inside dimensions of 1.5 inches x 2.5 inch and 1/16 inch thick, which acted as distillation draftstop. This draftstop also provided support for the glass cover. A 1/2 inch thick plate which covered the draftstop channels in order to



Figure 4 Mechanical stills.



Figure 5 Back view of the still.



Figure 10 Schematic of the glass-ceramic frame

assemble the distillation flask. The cover frame was welded together using argon-ion welding. This assembly cover facilitates in changing the type and giving access to the interior of the flask. The glass angle was kept 90° to the horizontal and facing north. This angle was decided so that it there should be sufficient condensing area and so the wall should intercept maximum radiation for a fixed angle throughout the year.

The south facing glass cover was double strength (1/8 inch thick) glass with dimensions of 1 ft. x 1 ft. Two of these panes were used for the front. The side glass covers were two right angle rectangular panes with dimensions of 1 ft.

The back plate was made of aluminum sheet (1/8 inch thick) and was bolted to the glass cover frame. This plate acted as reflector for solar radiation as well as condensing surface.

The glass panes and the back plate were then sealed to the frame by chlorine rubber sealant to make the cover vapor tight. The vapor tightness of the cover was then checked by passing water from a rubber hose over it and inside, if any, were then again sealed. In order that the wall be vapor tight after the cover is put over the basin, a coating of molten compressed paraffin¹ was run the entire length of the basin top. This compressed paraffin plastic over the temperature range of -100°F to 300°F had been used as a good sealant.

The water level in the stills was maintained by a constant head feed tank, shown schematically in Figure 11.

The basins were insulated on the sides by a polystyrene slab (Dinsmore²) which was 3/4 inch thick and dimensions of 1 ft. x 4 ft.



Figure 1. Floor plan of the laboratory room.

The bottom of each glass was attached to two 1/16 inch thick brass glass rings each having diameter of 8 in. x 4 in.

Thermocouples and Their Locations

Superconducting thermocouples of type 34 grade (2.5T) Inconel were used in all temperature measurements. Temperature measurements were made at various locations as shown in Figure 12. These thermocouples were attached on outside of the Plexiglas tank by a piece of Plexiglas strips and Eclonite diskettes, while on the glass cover they were held down firmly by transparent Scotch tape. This tape was used as electrical normal mycelium glass growing down on the thermocouple as shown schematically in Figure 13. Besides these locations thermocouples were attached on the inside of the insulation around the tank.

To measure temperatures of dry-matter in the still, three thermocouples were attached on a Plexiglas rod at various distances as shown in Figure 14. The thermocouple junctions were coated with a very thin coating of shellac to make them resistant to vacuum.

These thermocouples were calibrated, together with the temperature measurement monitors, at four temperatures, namely the ice point, and three other temperatures between 30°F and 130°F.

Insulating and Entry Isolations

There were about 30 thermocouples attached at different locations on both the stills and this necessitated the use of multiple seals.



FIGURE 1. Thermomagic Juggling on a 3D cube

Thermomagic Labelings

D_n the vertices of n -dimensional hypercube

A_n the vertices of n -cube and $n(n-1)/2$



Figure 14. Attachment of thermocouple to glass cover



Figure 16. Location of thermocouples in the water column.

measured). Incoming infrared radiation, by Koppell's and Lewis' (2) Leeds & Williams, were used. The Koppell's-Rosen thermocoupleometer had 10 points with accuracy of $\pm 0.2^\circ\text{F}$ and range of 0-100°F. The Leeds & Williams specimen chamber was 14 points with an accuracy of $\pm 0.2^\circ\text{F}$ and range of 0-100°F. These readings were contained in the mechanical chain so that the temperature readings could be taken after every 1. hour intervals.

The water collection data was received by Spauldy Physicochemical, Serial No. 14, and recorded on a single point Leeds & Williams specimen chamber with accuracy of ± 1 percent of the total scale. The additional temperature readings were obtained from the hypsithermograph at the Solid Energy Laboratory. This laboratory was about 10 miles from the site of the present experiments.

Identification Specimens of Spex

The Spex used in the present study were water soluble and supplied by Gaf Corporation. They were:

1. Naphthalene LB 88 (Black)
2. Carbazole 44 84 (Red)
3. Mixture of 10 percent by weight of each of the following dyes: Naprene E 3 (Blue), Carbazole 44 84 (Red) and Tartrazine C Basic (Yellow). This mixture resulted in dark blue dye.

The absorption spectrum from wavelengths of 0.3 μ to 0.75 μ was obtained using a Bausch & Lomb Model No. 14 spectrophotometer as shown in Figure 15, where Q2 is the spectrophotometer and Q3 is the strip



Figure 15 Baritone, VCR-121 repair replacement

large recorder for output data. The spectrum cell was a standard quartz rectangular cell with optical thickness of 4 cm. The absorption data for wavelengths from 8.75 μ to 12.5 μ were obtained using a Beckman-Quart Model D-1 Spectrophotometer as shown in Figure 18 with 141 the monochromator and 142 the entry slits connected with the recorder. The spectrum cell for this instrument was designed for the present study from Figure 173. It consisted of an aluminum alloy ring 1 inch in diameter and 414 inch in length and the thickness of the ring being 1/16 inch. This ring was sandwiched between 2 glass windows each of diameter 1 inch and thickness of 1/16 inch. To seal the assembly water tight rubber gaskets (1/16 inch thick) were put between the aluminum ring and the glass windows. This cell was held in place by aluminum supports, which were joined to each other. Figure 18 shows the recommended view of this cell.

The Beckman Spectrophotometer is a differential device wherein the spectrum of the spectrum is continuously compared with that of distilled water. Thus, it gives the transmittance spectrum [transmittance = log (incident radiation/transmitted radiation)] directly. However, the Beckman-Quart Spectrophotometer is not a differential device and thus separate readings of the transmittance spectrum of cell only, cell filled with distilled water and cell filled with dye sample, were taken. The absorption coefficient k_p was then calculated from these readings:

Experimental Procedure

The two cells were run side by side supported by a diameter of about 3 feet, as shown in Figure 19. They were filled with one meter



Figure 16. Spectral-DNA measurement.



Figure 17. Spectral cell.

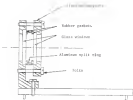


Figure 18. Cross section of the specimen cell used in Perkin-Elmer Resonance Raman.



Figure 11. Arrangement of the materials.

to the depth of 20.5 inches and the level was maintained by the feed tank. Carbon salt composition weighed, 3.5 percent by weight, was added to the two stills. In one of the stills, dye of known concentration was added. The waters were then put over the stills and allowed to stand for a day or two to obtain a steady periodic evaporation. After this period of time the distillate was collected every 24 hours and the weight of the distillate was measured by a analytical type balance with an accuracy of 0.01 lbs. The temperature measurements of various fractions were recorded on the rising stage of every 1 hour interval.

Three dyes were tested with concentrations of 50 ppm and 150 ppm for each except for the black dye where the testing was done for 50 ppm and 171.5 ppm concentrations.^a The duration of testing for each dye is given in Table 1.

In a number of instances the distillate was collected every hour so as to study its hourly variation. This also helped in calculating the constant C in equation (20), as will be shown in Chapter 7.

The absorption spectrum of the dyes before and after the duration of experiment was also obtained so as to study their degradation by sunlight. Also evaluated was the absorption spectrum of the distillate to study carry over of the dyes by water vapor.

The results of the experiment are presented in Chapter 8.

^aThe maximum concentration of black dye was supposed to be 150 ppm but the remaining dyes inadvertently resulted in 171.5 ppm concentration.

Table 1
 Location of $\mathbf{h}_{\text{opt}}$

Site	Demarcation 1/yr ⁰	Duration of Year
Carnegie (land)	50.0	11/28/77 - 11/28/78
	100.0	11/28/77 - 11/14/78
Wrightsville (land)	50.0	11/14/78 - 11/28/78
	175.0	11/28/78 - 04/14/79
Bank Green	50.0	04/14/78 - 08/14/78
	140.0	08/14/78 - 09/11/78

CHAPTER V

RESULTS AND DISCUSSION

The Absorption Spectra of Dyes

The absorption spectrum of different dye is shown in Figure-16 through 25 where the absorption coefficient ϵ_{λ} is plotted against wavelength λ . The absorption coefficient is a function of concentration of the dye and the temperature and pressure of the system. In the present analysis the temperature and pressure effects are ignored.

Figure 16 shows the absorption coefficients for 10 ppm Corundum (Red) dye¹ taken both before and after the experiment. This dye shows the dip in the absorption curve between 4.5 and 5.7 μ m which is the red part of the spectrum. Similarly in Figures 17 and 18, which show the absorption spectrum of the Black dye, the dip in the value of ϵ_{λ} occurs between 6.5 and about 9.515 μ m which is the blue region. Thus, this dye, strictly speaking, is a dark blue dye and not black. The dark brown dye, as has been pointed out before, was made up of a mixture of Erythros Blue, Carthagen (Yellow) and Corundum (Red) dyes. The dip in the absorption curve in the middle region, is at 7.5 μ m which is the green region of the spectrum (see Figure-19 and 21). Also shown in Figure 22

¹Appendix 111 shows the experimental set up for measuring ϵ_{λ} from experimental data.

Figure 10. About 100 *Hydrobia* on a flat stone (the pond).

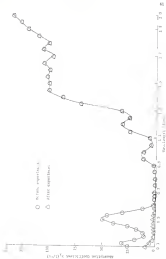


Figure 21. Absorption spectrum of lead dye (100 ppm)



Figure 20. Absorption spectrum of TiO_2 (A6-10) gel

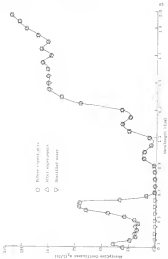


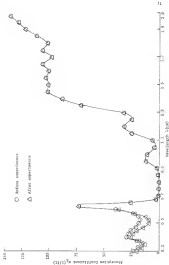
Figure (2): Serotypes spectrum of *Shigella* spp (1973-8 year)



Figure 14. Drawing of the (a) front view (b) left view (c) top view



Figure 10: Energy spectrum of atom Ar^{16+} (120 ppm)



in the absorption coefficient of distilled water. As can be seen, all the dyes tested in the present study have n_d very nearly the same as that of water above 0.7μ . This is to be expected, since above 0.7μ wavelengths well out of the range of the ionizing photon goes to the rotational, vibrational or translational modes of the energy of the dye-water complex. Since the amount of the dye is small ($<100 \mu\text{m}$), the absorption spectrum of the dye is very nearly the same as that of water. However, in the wavelength region of 0.7μ to 0.8μ there is still enough energy ($>1.5 \text{ eV}$) in the photon to produce higher n_d by changing the rotational-vibrational states of a suitable dye-water complex. The dyes tested in this study did not show this change, and thus there is a need to develop dyes which will have high n_d in this region since it contains about 35 percent of the total solar radiation.

The degradation of the dye by sunlight was studied by comparing their absorption spectrum before and after the experiment. Figure 10 shows n_d for Red dye at the end of the experiment. As can be seen there is severe degradation of this dye resulting in reduction of n_d by 35 percent at a wavelength of 0.5μ . This also resulted in the change of the color of the dye from bright red to an almost colorless liquid. The reason for this degradation appears to be photolysis caused by ultraviolet radiation. In the solar spectrum about 8 percent of this spectrum (ultraviolet region from 0.3μ to 0.4μ) is transmitted by the ordinary covered glass used. This can be determined more clearly by examining the molecule of the Carbazole (Red dye shown below,



where the $\text{ind}(\text{H})$ from dye is located at $\text{H} = 7$ atmosphere [29].

The bond strength of H-H is 1.48 eV [45] while the energy of the photon is 3.12 eV (wavelength is 3.95 eV) and thus the degradation of dye is favorable. However, no one single mechanism explains the fading of dye and involves three photochemical reactions—oxidation, reduction and photolysis. In the case of Carmoisine II is possible that both photolysis and oxidation reactions are possible for the fading. One possible oxidation is the change in pH of this dye, in 400 ppm concentration solution, from 5.2 (before experiment) to 5.7 (after experiment).

A similar degradation is found in the Dark Green dye as shown in Figure 14, where the degradation is primarily a result of the fading of the Carmoisine dye. The absorption coefficient of this dye drops by about 12 percent at 3.5 ps. This resulted in the change of the color from dark green to brownish green. The other constituents, namely Levamisole and Etoposide Blue, appear to be unaffected.

The most stable dye (among those tested) from the color degradation point of view appears to be Black Naphthylamine. For the duration of the experiment, its α_2 did not change as can be seen from Figure 15. The dye has the following structure:



It appears that the OH group attached with NH_2 is responsible for lightfastness of this dye [31]. However, no satisfactory theory exists

for which sufficient, or too high-fidelity with any degree of comparison and most of the information available is not supplied.

Temperature-Time History of the Ballie

The measured temperature-time history of the various dye-water systems are plotted in Figures 25-31. As can be seen from these figures, the general trend is similar and thus it would be sufficient to explain one of these figures. Figure 27 shows the temperature-time history of Black dye C61 (pH = 6.8) on March 6, 1975. The top layer temperature reaches a maximum of about 110°F around 8:30 p.m. (EST) whereas the maximum solar radiation is reached around 12:40 p.m. (EST). This lag in the top layer temperature is because of the mass of the dye-water system, the ambient temperature and the conduction of heat from this layer to the bottom mass. The glass temperature also follows the similar trend.

The bare aluminum plate temperature, however, rises very rapidly and reaches a maximum of about 130°F at 11:30 p.m. (EST) (Figure 25). As was mentioned before (Chapter 23), this plate's purpose was to reflect incident solar radiation onto the water still and at the same time act as a radiometer for water vapor. However, because of rapid oxidation of the plate the reflection property deteriorated rapidly thereby increasing its solar absorptance and hence its temperature. Because, it can be seen from Figure 27 that the plate temperature is greater than the water surface temperature till about 6:30 p.m. (EST) after which it rapidly approaches the glass water temperature. Thus

Figure 24. Temperature rise (solid line) (a) and dry (18) ratio (dashed line) (b), 1973.



Figure D - Temperature-time history of Black Sea (30 and 40
Barb 4, 1979)

Figure 20 Temperature-time history of Node 896 (270.3 yards)
March 24, 1964.

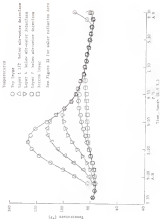


Figure 10. Temperature-velocity history of steam dye (50 gms), day 15, 1978.

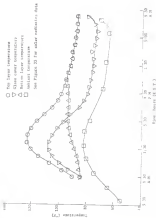
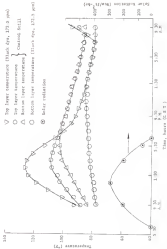


Figure 30. Superposition-of-line history of March 4th (120.3 mch.) April 14, 1871.



Figure 24. Representative history of the one military band (1959-1979).



and 4:30 p.m. (GMT) is confirmation that, given the above theory justifying the assumption for equations (18) and (21)

The temperature of the bottom layer, in the meantime, continues to rise above that in heat conducted down the top layer during cooling and also a small portion of incident solar radiation. It is noted by Li Allen about 3:30 p.m. (GMT) the top layer temperature falls rapidly, both because of rapid convection of water from the surface as well as the cooling of environment. At about 3:30 a.m. (GMT) the bottom layer temperature and top layer temperature merge. This is because after this time the conduction difference etc. set up and the water near-surface layer loses heat as a single mass. The intermediate layer also follows the same trend as shown in Figure 18.

The bottom layer temperature and the time at which it merges with the top layer temperature is an indication of the typical depth of the two-water system. As can be seen from Figure 18, for the Red Sea (20 ppm), the bottom layer temperature merges with the top layer temperature at around 5:30 p.m. (GMT) whereas the two temperatures for the Black Sea (170 ppm) meet around 5:30 a.m. (GMT) (Figure 19). This point can be further explained by looking at the incident solar energy absorbed in different layers of the two-water system. Figure 14 shows the percentage of solar energy absorbed in different layers at 10:30 p.m. (GMT). The Red Sea (20 ppm) absorbs about 15 percent of the incident solar energy in the top 1 inch layer, as compared to about 25 percent energy being absorbed by Black Sea (170 ppm) in the same layer thickness. This results in the top layer temperature in the Black Sea system being much higher, thereby prolonging the time of cooling.

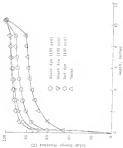


Figure 3. Percentages of water vapor absorbed with depth of solution April 16, 1955 at 12:30 p.m. (11 a.m.)

The above plot can be further classified by comparing the temperature-time history of the dye-water system with that of the control still. This comparison is shown in Figure 11 where the temperature of the top layer of black dye (1.75-3 ppm) and water are plotted for the same day, March 11, 1978. The top layer and bottom layer temperatures for control still drops around 8:30 p.m. whereas for dye-water system they drop at around 1:30 a.m. (EST). Again, this can be explained by Figure 12 where it can be seen that about 50 percent of the incident solar radiation reaches the bottom layer of the control still as compared to about 3 percent for dye system. Thus, the overheat occurs in the control still are set up earlier as compared to those in the still with dye. This also explains the difference in maximum temperature difference between the top layer and bottom layers for water only and dye-water systems. From Figure 12 one can see that the maximum temperature difference for black dye is about 44°F at 1:30 p.m. as compared to about 18°F for control still. This then leads to more uniform heating of the water in the control still and because of the heat of the system the top layer temperature drops less rapidly as compared to that of the dye-water system. Figure 13 shows the temperature-depth profiles for these two systems for different times.

Figures 14 and 15 show the plot of temperature-time history of the top layer temperature and glass cover temperature for dye-water solution and water only for two days. The higher temperature of the top layer of water during night (after 7:30 p.m. EST) as compared to that of dye-water solution results in higher temperatures for the glass cover. The higher top layer temperature is also an indication of the

Figure 13. Percentage prediction of removal of insecticides before March 31, 2019.

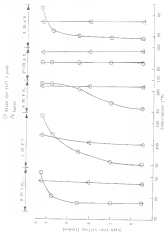


Figure 3: Supermodel-Cas history of the two sides, April 24, 2018.

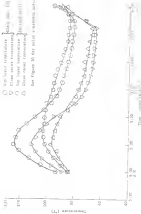
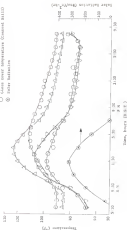


Figure 10 Temperature-time history of the test during May 15, 1998

- △ Top layer temperature (Glass dya, 50 100)
 ○ Top layer temperature (Electrol. Heill)
 □ Glass mirror temperature (Glass dya, 50 100)
 ⊙ Glass mirror temperature (Electrol. Heill)
 ⊗ Inher. Radiation



Inher. Radiation (Electrol. Heill)
 0 20 40 60 80 100 120 140

higher wet-bulb air sight from the control wall as compared to that from the wall with dye. This point will be further clarified in the next section.

Productivity of the Wall

One consequence of the temperature profiles explained above can be seen in the distillate output. Figures 26 and 27 show the histograms of the distillate output for the two systems for April 13 and May 21, 1978. Since the top layer temperature in the dye-water system temperature is higher than that of the control wall during daytime, the distillate output is higher (about $0.835 \text{ kg/m}^2 \text{ hr}$) for this system as compared to that from the control wall (about $0.648 \text{ kg/m}^2 \text{ hr}$). The maximum distillate for wall with dye is observed around 2:30 p.m. (GMT) (Figure 27) while that for control is at 12:30 p.m. Consequently, around 55 percent of the total distillate output for the dye system takes place during daytime (5:30 a.m. to 7:30 p.m.) as compared to that from the control wall where only 28 percent occurs during this time and 72 percent during the night. It is anticipated that because of the higher brine temperature at the control wall at night, greater heat loss occurs from the bottom and the sides of the wall, as compared to that from the wall with the dye. This results in lower evaporation for long-term wall (with smart output). Table 1 shows the comparison of evaporation, for wetness days, between the control wall and the dye wall.

The distillate output, however, depends both on the brine surface temperature and the temperature difference between the brine surface and

Figure 26. Scintillation spectra from milliwatt dye and mineral oil, April 23, 1976.



Figure 20. Standard output from shell with the and from control shell, May 13, 2019.



1997

Date	Sex	Age	Feet and Inches	Wing Length	Bill Length	Weight (gms)
November 26/17	Red	50	200/1	7 3/4	2 1/2	2.4
January 18/18	Red	100	200/1	8 5/8	2 5/8	10.8
March 17/18	Black	50	200/4	8 1	3 1/2	10.7
March 11/18	Black	175 1	24 3/4	11 7/8	3 1/2	17.1
April 24/18	Black	175 1	24 3/4	11 7/8	3 1/2	16.8
April 13/18	Black	175 1	24 3/4	11 7/8	3 1/2	16.8
May 14/18	Black	20	20 1/2	11 1/2	3 1/2	14.8
August 22/18	Green	100	20 1/2	11 1/2	3 1/2	12.8

1000

[illegible]

Approximate performance = $\frac{\text{Maximum Value} - \text{Minimum Value}}{\text{Maximum Value} - \text{Minimum Value}} \times 100$

the glass cover (10). Figure 28 shows the plot of h_{avg} vs time and ΔT vs time, where h_{avg} is given by the following equation:

$$q_u = h_{avg} A \Delta T \quad (44)$$

and q is given by equation (41). However, in order to calculate q_u , the value of coefficient K in equation (40) has to be found experimentally. This is done by comparing the distillate output v , calculated from the following equation:

$$v = h_a A (h_{1a} - h_{1g}) \quad (45)$$

where all the terms in this equation have been explained in Chapter IV. This v is plotted against the experimental value for two different days. From this plot the value of K is determined to be 0.07 for all cases except from 11:00 a.m. to 1:00 p.m., when it is 0.15. The two values take into account the changing conditions present inside the still because of condensation on the side glass cover and back plate. These values of K were then subsequently used in the analytical model, whose results will be explained later. Figure 29 shows the experimental and calculated distillate output using the above associated coefficient K .

Now q_u is calculated h_{avg} can be plotted against time (Figure 30). It can be seen that the profile of h_{avg} and ΔT has a maximum or around 10:00 p.m. (nearly, for water heated still) this maximum takes place around 11:00 p.m. (Figure 31), a fact which is confirmed experimentally (Figure 25).

From Figure 28 it is also evident that h_{avg} follows the trend of surface layer temperature T_g and hence a relationship between them may

Figure 16. Precipitation (mm) (vertical axis) and temperature (°C) (horizontal axis) from January to March 2015 (left) and April to June 2015 (right).

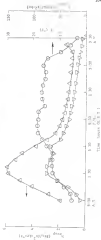




Figure 26 Temperature loss measurement-time history for control unit; (a) 15 (b) 20.

Figure 46. *Matellista indiana*. From blood agar (22) 5 weeks, April 14, 1974.



shown in Figure 40 shows such a relationship. Here the value of h_{evap} for various days and different dyes is plotted against the ambient temperature and the resulting empirical relation is given by

$$h_{\text{evap}} = 0.004 \exp [0.0005 (T_g - 1) \times 10^4] \quad (40)$$

where T_g is in $^{\circ}\text{F}$. However, a more meaningful relationship for a connection to the area of solar distillation is that of distillate output and T_g . Figure 41 shows such a relationship where the experimental distillate output has been plotted against T_g for various dyes and different days. The least square curve fitting the data is given by

$$D = 0.001 \exp [0.0005 (T_g)^2 - 0.011 (T_g)^2] \quad (41)$$

where T_g is again in $^{\circ}\text{F}$. There is a theoretical basis for such a plot. It has been shown in equation (32) that distillate output is a function of T_g and temperature of the glass T_g . However, these temperatures etc., in turn, functions of input solar radiation and ambient temperature. Finally, the ambient temperature is also a function of solar radiation and thus a relationship exists between distillate output and T_g . It should be noted that if the glass cover temperature of T_g is changed artificially then equation (41) is not valid. Thus, this equation holds only for passive type solar distillation units.

It is also instructive to analyze the different energy exchange mechanisms from the saline solution in the glass cover and the losses to the environment from the sides and bottom of the still. Figures 42 and 43 show different energy exchange mechanisms for the dye and control stills, respectively, for April 26, 1978. Each item is a percentage of

Figure 4: Correlations between $\hat{h}_{\text{avg}}$ and $\hat{h}_{\text{max}}$

$(\lambda_0 - \lambda_{\infty}) / (\lambda_0 - \lambda_{\infty})$ λ_{∞}

- Red dye, 50 ppm, November 26, 1951
- △ Blue dye, 250.0 ppm, April 16, 1952
- Yellow, April 16, 1952
- Green dye, 50 ppm, May 15, 1952
- Yellow, May 22, 1952
- ┘ Standard Error = 0.05

λ_{∞} (nm)

10 20 30 40 50 60 70 80 90 100





Figure 10. Correlation of Anisotropy Index and C_p

Figure 62

Analysis of energy transfer mechanism for Rhod dye
Dye : red April 16, 2019.

- Evaporation energy transfer
- Radiation energy transfer
- △ Combustion energy transfer
- Reaction rate (10⁴ s⁻¹)

Temperature (K)



Figure 14. Analysis of the energy transfer (percentage) (1971-1974)



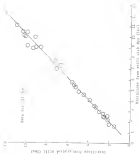
all the energy radiating by the long mechanisms arranged. As can be seen from these two Figures, greater compressions indeed come from a dry surface than from the wetted still surface. Also, the losses from the bottom wet surface to the control still are greater (about 30 to 35 percent of the total loss) as compared to those from the still with dry (about 5 to 30 percent of the total), (judged from the control still) the bottom and side losses are about 2-3 times those from the evaporator still. This is the cause of the lower efficiencies exhibited by the deep basin still with water only.

COMPARISON OF DISTILLATE RATES

As was pointed out in Chapter V before different data were tested, the two stills were filled with water only and their distillate outputs are compared. Figure 45 shows the correlation of distillate output of the two stills, and as can be seen they are identical.

The data are depicted in such order by comparing the distillate output from the evaporator system α_{ev} against that from the control still, α_{cl} . Both compressions have been made for different dry concentrations (Figures 46 to 50). The data have been plotted for completely clear and "nearly clear" days. Nearly clear day has been defined arbitrarily as a day in which the sun produces a shadow for at least 30 percent of the time. As can be seen from these Figures a linear compression line is used to fit the data points. However, the results from these Figures become meaningful only if some way of generalizing this is found so that the effect of a certain dry in increasing the compressions can be calculated.

Figure 15. Quantities known the performance of the system.



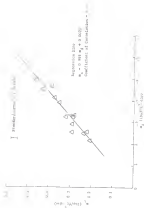


Fig. 1. Dependence of the rate of polymerization on the monomer concentration.

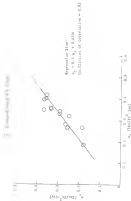
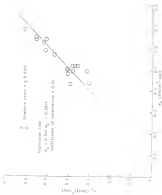


Figure 3.1 Comparison of dilution viscosity for Red Spruce (1200 ppm).

Figure 10: Comparison of dissolution energies for alkali and alkali earth



REPORT ON THE PROGRESS OF THE WORK OF THE COMMITTEE DURING THE YEAR 1900

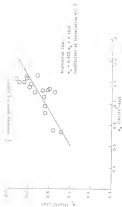
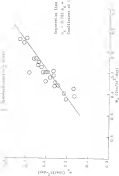


Figure 26. Comparison of distillation outputs for Green Eye (40 ppm).

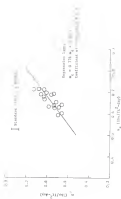
1) $\text{H}_2\text{O} + \text{H}_2\text{O} \rightarrow \text{H}_2\text{O} + \text{H}_2\text{O}$



Regression Line

$k_2 = 0.011 [\text{H}_2\text{O}] + 0.002$
Coefficient of Correlation = 0.99

Figure 5. Location of sampling points in the Gironde est (600 m).



A generalization exists in that attempted by selecting the slope β of the regression line, for different types, and the absorption of solar radiation by dyestuff system. From Figures 44-54, it can be seen that the slope decreases as the dye is changed from red to black. This is to be expected, since black dye absorbs more radiation at the surface as compared to red dye and hence increases the output. Figure 55 shows the plot of slope against a normalized absorption α , which is an indication of how well a dyestuff system absorbs solar radiation and is given by the following equation:

$$\beta = \frac{\frac{I_{\lambda_2}}{I_{\lambda_1}} \alpha_{\lambda_2} (L - \exp(-\alpha_{\lambda_2} x)) \sin \theta}{\frac{I_{\lambda_2}}{I_{\lambda_1}} \alpha_{\lambda_2} (L)} \quad (56)$$

where α_{λ_2} is given by equation 19 and L is the path length of the solar radiation in the dyestuff system. In Figure 56, α^0 is arbitrarily taken as 0.51 inch. Thus, as x increases the slope β decreases and the relationship is given by the following regression line,

$$\beta = 1.644 - 0.028 x \quad (57)$$

with a standard error of ± 0.021 .

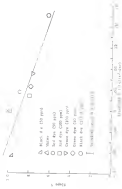
Figure 57 presents the slope β versus the distance x of various regression lines (Figures 44 to 54). This relationship is given by the following regression line:

$$\beta = -0.0736 x + 0.1139 \quad (58)$$

with a standard error of ± 0.0029 .



Figure 10. Correlations between stage 3 and subsequent β



- ☐ A Mark is a 100 yard
- ☐ B Mark
- ☐ C Mark 100 yard
- ☐ D Mark 100 yard
- ☐ E Mark 100 yard
- ☐ F Mark 100 yard
- ☐ G Mark 100 yard

1. The amount of money earned is 100 dollars.

Thus, by using equations (40) and (44) the percentage increase in compensation can be evaluated in the following manner. If the distillate output from the control unit is $n_d(15\pi/T)^{1/2}$ days and that from the dysenteric system is $n_d(15\pi/T)^{3/2}$ days, then the percentage increase (I) in compensation is given by:

$$I = \frac{n_d(15\pi/T)^{3/2}}{n_d} \times 100 \quad (45)$$

and if the equation of the regression line is written in the form

$$n_d = \ln_d + k \quad (46)$$

then,

$$I = \left(\frac{1}{n_d}\right) \ln_d + \frac{k}{n_d} \times 100 \quad (47)$$

Thus, for any day when $\bar{x}$ is known (which can be found from the absorption spectrum) the percentage increase in compensation can be found using equations (45) through (47). From equation (44) it is evident that this increase is dependent on the distillate output from the control unit, n_d .

An attempt was also made to plot n_d and n_g for different months of the year (see Figures 36 and 37). It is obvious that the variation of n_d varies in time, since the water utilization is also variable at this time. It should be pointed out that the above equations for percent addition are only valid when the outputs from dysenteric species are compared from an equivalent interval, still of days 10-5 (which is from Figure 34 and 35) the distillate output is far more and usually



Figure 14. Annual variation of the abundance of four species (A, B, C, and D).



Figure 8. Dimensionless function $f(\eta)$ for various values of η .

clear dye) [16] is known. Diffic is so difficult to separate from both the walls or completely cloudy dye (dye when the sun did not produce any stain) as shown in Figure 16. The reason for the two outputs is by the same as a cloudy dye is not difficult to see, since in such a dye the amount of reflection reaching the water surface is very small (about 5 percent of the clear dye reflected and diffuse) and thus is absorbed mostly on the surface of the water, thereby making their outputs nearly identical.

Finally, the simulated spectrum of the distribution from dye-water system is plotted in Figure 59. This is done to ascertain whether there is any carry-over of the dye molecules. As can be seen from this figure there appears to be no indication of such a carry-over. This is to be expected since these dyes have boiling points of about 180°C and above [42], whereas the maximum surface temperature recorded for dye-water system has been about 120°C and thus only water evaporates. However, because of gaseous evaporation from the water surface, there is no carry-over of the dye by convection currents.

Comparison of Predicted and Experimental Results

The computer program for the simplified model was run for various dyes to compare the predicted temperature-time history of the dye-water system with that obtained experimentally. The input to the program included the water circulation, ambient temperature data, wind velocity, value of coefficient k in equation (20) and the value of average concentration $\bar{C}_{B/W}$ for each dye (record given above). The water

Figure 34: Black-hole images from two orbits on completely cloudy days.

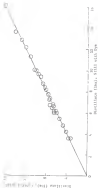




Figure 17. Absorption spectra of distillation from various dates.

galaxies and the ambient temperature data were included in the program by polynomial regression. These polynomials fitted the data well (scatter error was ± 2 percent). The determination of the coefficient C has already been explained. The value of $\bar{T}_{\text{sky}}$ was experimentally obtained by using a first law of thermodynamic analysis on the soil, and after making corrections for the reflection losses of long-wave solar radiation from the water-air interface. This correction was made using equation (11) and an average reflection loss of 12 percent from the water-air interface was obtained. With this analysis the value of $\bar{T}_{\text{sky}}$ was obtained as 3.71, which was subsequently used in the program. It should be pointed out that this is an average value for the whole day and will obviously change during the day, but for simplicity it has been used as such. The thermophysical properties such as the water-vapor diffusivity, density, etc. have been calculated as an average temperature of 100°F (see equation 1 for data compilation).

The comparison of temperature-time history for dry water systems, between calculated and experimental results, for different dyas, is plotted in Figures 34 to 37. As can be seen from these figures, the agreement between the calculated and experimental results is excellent. However, for hot dyas (Figure 36) there was a slight difference (about 4%) between the calculated and experimental temperatures of the top layer, after 1.50 a.m. This difference can be attributed to lower wind velocity used in the program and approximation used in the value of coefficient k [equation (10)]. The wind velocities used for computer simulation were average for the whole day. However, on certain days there were considerable fluctuations in the wind speeds during day and

Figure 14. Competition between *S. nemoralis* and *Myrica gale* ssp. *repens* for both dry (2000) and wet (2011) seasons. 16.



Figure 20: Respectively between Disagreement and disagreement result.
 For $\text{Kant}_{\text{dis}} = 150$ and $\text{Kant}_{\text{dis}} = 175$.



Figure 10. Comparison between theoretical and experimental results for Blank dye (11.13 ppm), March 90, 1998.



Figure 11: Comparison between theoretical and experimental results for the case of $\alpha = 0.5$ and $\beta = 0.5$.



Time, hours of day

1:40

1:50

2:00

FIGURE 4-10 Comparison between the traditional and new financial systems for Green Day Oil and Gas, May 15, 2011.



light and this lies 1.5-2.0% of the former; (ii) the difference between the calculated and experimental temperatures.

The maximum calculated temperature difference for conventional heat transfer between the bottom and the top layers in the dry-wet system was about 4.5°F , which is within the maximum accuracy range of the resistance and thus was not observed experimentally. However, even so this temperature difference the apparent conductivity as calculated from equation (10) is about 20 times the value of thermal conductivity of water. This then resulted in producing nearly the same temperatures for the layers.

Figure 82 is the plot of temperature-time history for Green dye. There is about 4°F difference between the predicted and the experimental values of the top layer temperature around 4.50 p.m. This can be attributed to the uncertainty in the value of α_{eff} . As was pointed out earlier that dye molecules degenerate by sunlight and in the streams of the boundary about the rate of degradation, an average value of α_{eff} before and after the experiment was used.

Finally, the temperature profile for black dye (170 g/gal) for Run 33, 1978, is plotted in Figure 83, showing the comparison between the calculated and the experimental results. The calculated top surface temperature is slightly lower (about 1°F) than that of layer 1/3 inch below because of convection cooling. There is a difference of about 4°F between the calculated and experimental top layer temperature around 4.50 p.m. This can again be attributed to the approximation of coefficient C and wind calculation. It should be pointed out that the predicted output calculated from the computer program is within ± 20 percent of the experimental value.

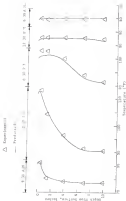


Figure 4. Comparison between theoretical and experimental temperatures, per cent for alkali-free GPT-3 using Norrish 24, 1954.

Effect of Various Variables on Solid Interdiffusion

One additional coefficient is involved in the validity of the solidified model. It is appropriate to investigate the effect of various parameters like solute temperature, wind velocity, and various surface conditions of different types, on the probability of solid state.

Effect of Solute Temperature

The effect of various solute temperatures dependent on percent of the solid solvent temperature, T_{sol} for March N. 2518 (black dye, 1/2 S used as diffusive output) is plotted in Figure 16. As can be seen from this figure a decrease in T_{sol} by 10 percent decreases the diffusive output by 10.1 percent, while an increase of T_{sol} by 10 percent decreases the output by 10.8 percent. This is to be expected since conduction of diffusion on a glass cover is primarily a function of the temperature difference between glass and surface, for the heat transfer heat transfer coefficient. This result is similar to some of the results of theoretical and experimental studies [18] done noted in solid diffusion literature, where it is reported that increasing the solute temperature increases the probability of the melt. The justification for this has been provided by kinetic argument that as increase in solute surface temperature results with increase in solute temperature, thereby increasing the diffusive output [19]. However, it should be pointed out that the solute surface temperature does increase with increase in solute temperature but the temperature difference between the vapor surface and the glass cover (the driving potential for mass transfer) decreases. Figure 17 shows the plot of

Figure 14. Assignment plot of the effect of ambient temperature on simulation output, Burdell *et al.*, 1998.



Figure 15. isothermal plot of the temperature-time history for black dye (111) 3 ppm, cards No. 100, for two additional temperatures.



surface temperature T_s of the water surface and the difference between the temperatures of surface and glass water film for the selected temperatures. The difference in surface water temperatures for above two conditions is about 40°F (about 90 percent increase in temperature, for higher surface temperature conditions, even than the lower surface temperature condition) at about 11.32 p.m. QNTI shows the $h_{\text{conv}} = T_s^{-1}$ for lower surface temperature condition is 4 times that for higher surface temperature condition. It has been pointed out before, convection heat transfer is a product of h_{conv} (function of T_s) and ΔT and that the lower surface temperature condition results in higher convection heat than greater (predicted) convection to the higher surface temperature condition.

EFFECT OF Wind Velocity

The effect of wind velocity on distribution output for the wind is plotted in Figure 54. There is no increase in output by about 13 percent with wind velocity increasing from 0 to 13 mph. This is because there is better heat transfer from the glass cover to the surface. However, with increasing wind velocity (about 13 mph) the output starts increasing. The reason for this is that at higher wind velocities the distribution is best transfer is imposed by the conduction of glass and not by the outside heat transfer conditions. It should be pointed out that there are conflicting results presented in the literature on the effect of wind velocity on productivity [18]. However, some computer simulation results [20] do confirm the increase of productivity with increasing wind velocity.

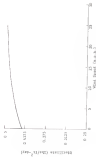


Figure 10 Analytical plot of the effect of wind speed on distribution output) March 6, 1979

Effect of Dye Concentration

The effect of various dye concentrations on distillate output for the three dyes is plotted in Figure 42. At zero ppm concentration they have the same output, and as the dye concentration increases, different dye-water systems exhibit different outputs with Black having the highest distillate while Red having the lowest. This is because of better absorption of solar energy by Black dye as compared to Red. However, after about 500 ppm there is no difference in distillate output from various dyes, since around this concentration level about 91.8 percent of the incident solar radiation is absorbed within the first 2.7 inch layer of dye-water mixture, thus making the composition independent of the volume of dye. It is also interesting to mention the surface temperature and bottom layer temperature variation for Black dye with 50 ppm and 400 ppm concentrations (Figure 43). Besides the higher surface temperature for 400 ppm concentration, an interesting point can be seen in the bottom layer temperature for the two concentrations. The maximum variation in bottom layer temperature for 400 ppm concentration is 1°F while for 50 ppm concentration it is 1°F . These temperature variations are an indication of heat losses from the bottom and sides of the still, which are ultimately reflected in the productivity of the still. Thus, in a way the above point is an indication of the effect of depth of the dye-water system on productivity, since by increasing the concentration of dye the effective depth of the still is increased while with decreasing concentration of the dye the depth is decreased. Thus, it can be concluded from this experiment that for the same concentration of dye, increasing the depth

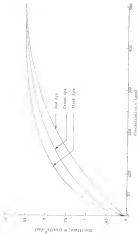


FIGURE 6) Analytical plot of the effect of eye concentration on distillate output, April 26, 1954



Figure 10. Calculated plots of the temperature-time history for 400 a/o, April, 14, 1978, for two different a/o concentrations.

depth will increase the probability [26, 24, 25] it can be shown that if the depth of the basin is greater than 20 inches, then the bottom layer temperature remains unchanged during a 24 hour cycle.

For the researchers in the solar distillation area, the important piece of information from the above study is how accurate of the optimum cost benefit ratio of using a particular dye. The problem is one of finding the lowest concentration, C , that will achieve a high output, Q , and is is therefore especially sensitive to the rate of change of output with concentration, $\frac{dQ}{dC}$. or in symbolic form,

$$\psi = \psi(C, \frac{dQ}{dC}, \lambda) \quad (34)$$

In the present study a particular form of this function is proposed

$$\psi = \lambda \frac{dQ}{dC} + K \quad (35)$$

Figure 15 shows the plot of equation (34) with λ equal to 1. Note this plot the concentrations of black, brown and red dye below the value of ψ is constant are 220, 197 and 440 gpc, respectively.

The optimum concentration increases from black to red dye, an observation as is expected since a lower concentration of black dye (because of better absorption of solar energy) gives the same distillation output as a higher concentration of red dye. These optimum concentrations correspond to distillate output of 0.011 lbs/Hr²/sq. ft. 0.012 lbs/Hr²/sq. ft. and 0.013 lbs/Hr²/sq. ft. for black, brown and red dyes, respectively. Thus, an increase of about 1.2 percent in distillate output of brown dye over that from black dye is achieved at the cost of increasing the



Figure 11. Variation of the ratio of the maximum to the minimum value of the function $f(x)$ versus the parameter x .

equilibrium of total dye over blank dye by 71 percent, which is directly reflected in the area of the dye. It should be pointed out, however, that the above criteria for optimum transmission are only valid for that particular day (April 18, 1975) and wind strength and season, with the largest value of dye concentration for a particular dye being in winter and lowest in summer.

CHAPTER VI
IMPROVED dye incorporation

Conclusions

The following conclusions can be drawn based on the present investigations, points 1 to 3 are based on experimental data, while points 4 to 6 are extrapolation on the empirical model.

1. By using water-soluble dyes the productivity of deep textile color will not be improved, by as much as 20 percent. The black dye with concentration of 274.5 ppm, even that of a mill with no dye.
2. During the dyeing process, Black Naphthylamine dye has been found to be most suitable, both from the point of view of increasing the penetration and lightfastness.
3. There is rapid fading of the Red Carmine dye under sunlight. Thus, at one month of exposure to sunlight the α_0 at 0.5 m wavelength is reduced by 55 percent. The brown dye also exhibited slight degradation and thus reduction in the α_0 at 0.5 m wavelength. This can be attributed to the Red Carmine dye degradation (50 percent by weight).
4. Based upon the experiments, a simple method of calculating the percentage increase in penetration by using a dye over time

can be shown that the two derivatives become ± 140 to ± 200 .

7. An empirical relationship has been developed for h_{app} and dilution output as a function of log layer temperature T_{L2} and is given by equations (32) and (33), respectively.
8. There is an increase in the dilution output from the mixed cell and the cell with dye as a function of steady day.
9. An analytical model which predicts the temperature-time history of the dynamic system has been developed and the agreement between the results from it and the experiments is excellent over the range of parameters investigated.
10. The analytical model predicts a decrease in dilution output with increasing ambient temperature. Thus, a 10 percent increase in the ambient temperature results in a 15.2 percent decrease in output.
11. The effect of wind speed on dilution output, as predicted by the analytical model, is an increase in dilution output with increasing wind speed. Thus, output increases by 30 percent with the increase in wind speed from 0 to 15 mph.
12. An increase in dilution output occurs with increasing concentration of dye till 500 ppm, after which it is independent of the concentration. However, the rate of increase of output with concentration is different for different dyes with blue having the maximum rate and Red dye having the lowest.

- ii) A method of predicting an optimum concentration of a particular dye, at the point where the sum of the rate of decrease of absorbance with concentration times concentration and the absorbance with concentration is maximum, has been developed for the dyeing conditions at Gainesville, Florida, the optimum concentrations for Black, Green and Red dyes were 240, 200 and 400 ppm, respectively.

Recommendations for Future Investigations

1. It will be worthwhile to develop water soluble dyes which have higher n_d in the wavelength range of 0.7 to 0.8 μ and have higher λ as compared to those used in the present study. Besides higher λ an attempt can also be made to develop dyes with greater lightfastness so that there is no degradation by sunlight.
2. A worthwhile effort would be to study the effects of dye-solvent medium complex on sorption of water. Studies of molecular structure, the surface tension of water and with better description of water sorption near the water surface with addition of dyes, there is a possibility of enhancing the sorption of water. Besides the absorption of the surface absorbency, an effort should also be made to study the effect of molecular disturbances on sorption.
3. An effort should also be made to look at different ways, both chemical and physical, of extracting the dye from concentrated brine or so to crystals or success in separating the dye by

sufficiently prove whether the use of dyes in large scale color distillation plants is economically feasible or not.

4. Besides the use of these dyes in color distillation it appears to be advantageous to use them for disposal of effluents from chemical plants, by sorption.
5. There also appears the possibility of using these dyes in liquid color reactions.

APPENDIX I

PROPERTY VALUES USED IN ANALYTICAL MODEL.

APPENDIX 1

PROPERTY VALUES USED IN ANALYTICAL MODEL

α_v	Thermal diffusivity of water = $1.41 \times 10^{-6} \text{ m}^2/\text{sec}$ [30]
α_{glass}	Solar absorptance of 1.5 mm thick glass = 0.07 [41]
β	Thermal expansion coefficient of water = 6.1×10^{-5} ($1/^\circ\text{C}$) [38]
$c_{p,\text{glass}}$	Specific heat of glass = $0.1 \text{ Joules/m}^3\text{K}$ [42]
$D_{v,a}$	Binary diffusion coefficient of water vapor in air = $1.56 \text{ m}^2/\text{sec}$ [43]
$h_a T_a$	= 8.81
$h_{v,g}$	Boiling heat transfer coefficient of water = $1000 + 0.016(10-30) \text{ Watts/m}^2\text{K}$ where T is in $^\circ\text{C}$ [44]
h_c	Outside convection heat transfer coefficient = $1 + 10.4 V_c \sqrt{\frac{100}{1000 T_c}}$ where T is in m/s [45]
k_v	Thermal conductivity of water = $0.364 \frac{\text{W}}{\text{mK}} \sqrt{\frac{100}{1000 T_c}}$ [36]
k_{vib}	Thermal conductivity of water-vapor mixture = $0.048 \frac{\text{W}}{\text{mK}} \sqrt{\frac{100}{1000 T_c}}$ [36]
k_g	Thermal conductivity of glass = $0.10 \frac{\text{W}}{\text{mK}} \sqrt{\frac{100}{1000 T_c}}$ [41]
k_{ps}	Thermal conductivity of Plexiglas = $0.191 \frac{\text{W}}{\text{mK}} \sqrt{\frac{100}{1000 T_c}}$ [47]
k_{poly}	Thermal conductivity of polystyrene = $0.0120 \frac{\text{W}}{\text{mK}} \sqrt{\frac{100}{1000 T_c}}$ [44]
n_1, n_2	Indices of refraction for air [4] and water [1, 20], respectively

η_w	Kinematic viscosity of water = $0.74 \times 10^{-6} \text{ m}^2/\text{s}$ [36]
η_o	Kinematic viscosity of silicone oil/water = $0.74 \times 10^{-3} \text{ m}^2/\text{s}$ [36]
ρ_w	Density water given by the following equation [36]
	$\rho_w = \rho_{w_0} + \Delta \rho = \left[\frac{1}{1} \left(\frac{64.1 + 0.75 T_w + 0.0001 T_w^2}{1 + 0.0001 T_w} \right) \right] \times 10^{-3} / \text{m}^3 \quad (34)$
	where
	$\rho_{w_0} = 999.842 \times 10^{-3} \text{ kg/m}^3$
	$T = t + 273.15, \text{ } ^\circ\text{K}$
	$\Delta \rho = 601.92 - T$
	$T = \text{temperature of the water, } ^\circ\text{C}$
	$\mu^* = 3.8419$
	$\mu^* = 3.8419 \times 10^{-3}$
	$\sigma^* = 1.42941 \times 10^{-6}$
	$\sigma^* = 1.42941 \times 10^{-3}$
$\text{Re}_{w/o}$	Froude number of water-oil mixture = 0.46 [36]
λ_o	Wavelength of surface wave = 140 cm/s^{-1} [42]
λ_w	Froude number for water-air mixture = 0.41 [36]
Re	Product of overall heat transfer coefficient and perimeter of the coil = $1.34 \frac{\text{W}}{\text{cm}^2 \text{ } ^\circ\text{C}}$

APPENDIX 11

ANALYSIS OF DATA FOR DIFFERENCE EQUATIONS

APPENDIX II

NUMERICAL SOLUTION FOR DIFFERENTIAL EQUATIONS

In the derivation of the stability criterion for the differential equations formulated in Chapter III, the method of Ingerf [9] is followed. The model equation for $\alpha^{(2)}$ layer is

$$\begin{aligned} \dot{Q}_{\text{tot}} = & \frac{1}{2} \frac{d(\bar{Q}^{(2)} - \bar{Q}^{(1)})}{dt} + \frac{1}{2} \frac{d(\bar{Q}^{(2)} - \bar{Q}^{(1)})}{dt} = (\frac{\bar{Q}^{(2)} - \bar{Q}^{(1)}}{2 - \alpha}) \dot{\alpha} + \\ & \alpha \frac{d}{dt} (\frac{\bar{Q}^{(2)} - \bar{Q}^{(1)}}{2 - \alpha}) \end{aligned} \quad (14)$$

where

$$\bar{Q}_{\text{tot}} = \bar{Q}^{(2)}_{\text{tot}} - \bar{Q}^{(1)}_{\text{tot}} = \int_{\text{tot}} (\bar{Q}^{(2)}_{\text{tot}} - \bar{Q}^{(1)}_{\text{tot}}) \exp(-\alpha_f \alpha^2) d\alpha$$

and the steady state solution of equation (14) is

$$\begin{aligned} \dot{Q}_{\text{tot}} = & \frac{1}{2} \frac{d(\bar{Q}^{(2)}_{\text{tot}} - \bar{Q}^{(1)}_{\text{tot}})}{dt} + \frac{1}{2} \frac{d(\bar{Q}^{(2)}_{\text{tot}} - \bar{Q}^{(1)}_{\text{tot}})}{dt} = \frac{1}{2} \frac{d(\bar{Q}^{(2)}_{\text{tot}} - \bar{Q}^{(1)}_{\text{tot}})}{dt} \\ & \alpha \dot{\alpha} \end{aligned} \quad (15)$$

Substituting equation (11-12) from (14) yields

$$\frac{k_{\text{eff}}^{\text{LAM}} - \frac{\gamma^L}{\Delta}}{\Delta} + \frac{k_{\text{eff}}^{\text{LAM}} - \frac{\gamma^L}{\Delta}}{\Delta} + \frac{(\frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta})}{\frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta}} = \frac{\gamma^{\text{LAM}}}{\Delta} \quad \text{as } \Delta$$

$$\frac{(\frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta})}{\Delta} \quad (11-1)$$

Since steady state temperature $T_{\text{top}}^{\text{LAM}}$ will be greater than $T_{\text{top}}^{\text{LAM}}$ then,

$$\frac{\gamma^{\text{LAM}}}{k_{\text{eff}}^{\text{LAM}}} - \frac{\gamma^L}{\Delta} \geq \frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta} \quad (11-2)$$

Rearranging equation (11-2) then leads to:

$$\frac{\frac{\gamma^{\text{LAM}}}{k_{\text{eff}}^{\text{LAM}}} - \frac{\gamma^L}{\Delta}}{\frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta}} = \frac{\Delta}{\Delta} \frac{k_{\text{eff}}^{\text{LAM}}}{\Delta} \frac{\Delta}{\Delta} \geq 1$$

$$\left[\frac{\frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta}}{\frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta}} \right] \quad (11-3)$$

Again, the scaling criterion for equation (11-3) is:

$$\Delta \leq \frac{\frac{\gamma^{\text{LAM}}}{\Delta} \frac{\Delta}{\Delta}}{\left[\frac{\frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta}}{\frac{\gamma^{\text{LAM}}}{\Delta} - \frac{\gamma^L}{\Delta}} \right]} \quad (11-4)$$

Thus, with a temperature difference of 2.5°K between the bottom surface of the wall and the top surface of water (this gives the smallest value of apparent conductivity k_{eff} of $0.1 \text{ W/mK}^{0.75}$) and the layer thickness Δ of 1 inch, equation (11-4) results in:

for $\frac{1}{2}$ -ton ton...

100-00

In the program the value of 0.00 ton; but it was subsequently used.

A similar sort of mistake in the glass cover yields the value of $h = \frac{1}{2}$ ton and then $h = 0.01$ ton, the minimum value of the ton, was used.

APPENDIX III

OSCILLATION OF RESONANCE COEFFICIENT OF
SPE. SOLIDUS

APPENDIX III

TRANSMISSION OF INCIDENT COHERENT LIGHT ON BOUNCES

The transmission of the collimated radiation (the Fraunhofer-Machometer) can be found using the method outlined below. Figure III-1 shows the ray-trace diagram of the coll and attenuation of incident beam on glass 1-2.



Figure III-1: Attenuation of incident beam through glass.

The spectral transmittance of glass plate 1-2 can be written as,

$$T_{1-2} = n_2^2 \frac{(1-r_1^2)(1-r_2^2)}{(1-r_1^2 r_2^2)} \left[1 + r_1^4 r_2^2 + r_1^2 r_2^4 + r_1^6 r_2^2 + \dots \right] \quad (III-1)$$

or

$$T_{1-2} = n_2^2 \frac{(1-r_1^2)(1-r_2^2)}{(1-r_1^2 r_2^2)} \quad (III-2)$$

where

and Γ is optical admittance of incident medium is given by

$$\Gamma = \mu_0 \epsilon_0 c_0$$

ϵ_1 = optical refractive index of dielectric medium

ϵ_2 = optical refractive index of dielectric medium

Similarly the transmittance T_{D-2} and T_{D-4} can be written as,

$$T_{D-2} = \alpha_2^{-1} \frac{(1-\alpha_1)(1-\alpha_2)}{(1-\alpha_1)^2 \epsilon_1 \epsilon_2} \quad (111-20)$$

where

$$\alpha_2^{-1} = \text{optical admittance of incident medium by the medium} = \mu_0 \epsilon_2 c_0$$

and

$$T_{D-4} = \alpha_4^{-1} \frac{(1-\alpha_3)(1-\alpha_4)}{(1-\alpha_3)^2 \epsilon_3 \epsilon_4} \quad (111-21)$$

Therefore the overall transmittance for the cell-water solution is

$$T_{\text{cell/wr}} = T_{D-2} T_{D-4} \quad (111-22)$$

or

$$T_{\text{cell/wr}} = \left[\frac{\alpha_1^{-1} (1-\alpha_1)(1-\alpha_2)}{(1-\alpha_1)^2 \epsilon_1 \epsilon_2} \right] \left[\frac{\alpha_3^{-1} (1-\alpha_3)(1-\alpha_4)}{(1-\alpha_3)^2 \epsilon_3 \epsilon_4} \right] \left[\frac{\alpha_5^{-1} (1-\alpha_5)(1-\alpha_6)}{(1-\alpha_5)^2 \epsilon_5 \epsilon_6} \right] \quad (111-23)$$

where $\epsilon_1 = \epsilon_2$ and $\epsilon_3 = \epsilon_4$, T_{cell} is then given by the following equation

$$T_{\text{coll/pe}} = \frac{\alpha_1^{*1} \alpha_2^{*1} (1-\alpha_2^{*1})^2 (1-\alpha_1^{*1})^2}{(1-\alpha_1^{*2}) \alpha_2^{*2} (1-\alpha_2^{*2}) \alpha_1^{*1} (1-\alpha_1^{*2}) \alpha_2^{*1}} \quad (117-3)$$

then knowing the values of T_{coll} (eq. 117-1) and $T_{\text{coll/pe}}$ (eq. 117-3) with eqs. (117-2) the optimal absorption coefficients α_2^* can be calculated from equation (117-1).

REFERENCES

1. Falkowski, E. and Lindler, E. Water for a Thirsting World, West View Press, Boulder (1971), pp. 12.
2. Nelson, W. "Relating Needs and Resources in the Use of Water," Proceedings of the Study Week on the Fundamental Aspects of Water, April 24-28, 1975 (28- Füssen, B.), Elsevier Scientific Publishing Group, Amsterdam (1976).
3. Billingsley, E. and Billingsley, A. "Water Desalination," WaterResources **11**, 661-672 (1976).
4. Davis, E.W. "Desalination of Sea Water," Chemistry and Industry, 6, August (1977).
5. Anonymous "New Germany in For Solar Desalination Plant in Saudi Arabia," Times of India, 24, March (1978).
6. Egan, L.P. and Thomas, G.W. "Fundamentals of Water Desalination," in Solar Water Desalination (M. Saphir, J. A.S.J., Academic Press, New York (1971)).
7. Rethis, G. and Renaud, G. "A Short History of Water Desalination," Proceedings of the International Symposium, Willem, April 1981, 120-122 (1981).
8. Harding, J. "Appetites for Solar Desalination," Proceedings of Institution of Civil Engineers, **71**, 286-288 (1981).
9. Tielens, L.B., Harding, J.A., Lee, C.H.H., Wong, G. and Massey, J.W. Report on Solar Desalination of Seawater, Research and Development Program Report No. 126, United Nations Department of Economic, April (1978).
10. Egan, L.P. and Thomas, G.W. "Energy Factor of Rank on Solar Desalination in University of California," Solar Energy, **21**, 23-28 (1978).
11. Tielens, L. Report on Methods for Solar Desalination, Research and Development Report No. 13, Office of United Nations, United Nations Department of Economic (1978).
12. Jeffrey, J.P. "Partial Solar Desalination," Solar Energy, **11**, 275-278 (1971).

13. Chilling, J. J. and Collins, J. L. "Sound Wave Effects," Symposium on Heat and Fluid Instability of Boiling Two-Phase Mixtures, Report No. 10, Office of Naval Research, United States Department of Defense, May (1964).
14. Swenson, R. "Solar Still with Low Humid Current," Solar Energy, 15, 415-421 (1970).
15. Kelish, S. S. and Rajagopal, A. K. "The Effect of Suspended Condensation on Glass Solar Collectors," Solar Energy, 22(4), 399-393 (1977).
16. Blomer, J. P. "Factors Affecting Solar Still Performance," ASME Paper 84-WA/Solar-1, 8 pages (1984).
17. Barlow, C. F. "Thermohydraulic Behavior of Film Boiling Solar Still," Solar Energy, 20(2), 71-82 (1976).
18. Lee, S. H. C., Chilling, J. J. and Blomer, J. P. "Energy Balance in Solar Still," ASME Journal, 93(2), 442-449 (1971).
19. Chan, T. S. "Trough Collectors," United Nations Conference on New Sources of Energy, Paper 11/5/69, Rome, 42 pages (1969).
20. Blomer, J. P., Chilling, J. J., Lewis, J. S., and Lee, S. H. C. "Analytical Computer Simulation of Solar Still Operation," ASME Paper 82-WA/Solar-113, 8 pages (1982).
21. Talbot, M. "Fresh Water from Sea Water by Solar Distillation," Industrial and Engineering Chemistry, 53(10), 1458-1474 (1961).
22. Chilling, J. J. "Optical Modeling of Truncated Solar Still Processors," Solar Energy, 23(4), 313-324 (1979).
23. Chan, T. S., Rogers, R. B. and Thompson, T. L. "Operating Experiments with Natural and Forced Convection Solar Stills," Water and Space Tech., 10(2), 579-582 (1968).
24. Smith, R. V. "Solar Water Distillation: The Good Type Still and a Multiple Effect Rectification Still," International Developments in Heat Transfer, ASME, 1971-1972 (1972).
25. Smith, R. and Barlow, C. F. "Solar Stillification of Salt Water by Porous Tubes Using a Flowing Air Stream," Solar Energy, 13(1), 25-31 (1969).
26. Chilling, J. J. "A Method of Producing Fresh Water by Means of Solar Energy," Student's thesis, College of Engineering, University of Florida (1964).
27. Block, R. B., Barlow, C. F. and Springer, R. S. "Solar Desorption of Salt Water," Industrial and Engineering Chemistry, 53(10), 2494-2500 (1961).

- (24) Gordon, J. G. Personal communication.
- (25) Gordon, J. G. "Biological Correlations of a Retained Immune Response," Annals New York Acad. Sci. 21:42 (1974).
- (26) Gordon, J. G. Personal communication.
- (27) Kasper, C. C., Longmire, W. B., Connel, R. B., Goodwin, J. B., Berg, C. S., Kasper, W. B. and Olson, W. B. Diagnosis of Disease by Stool Excretion Tests. McGraw-Hill, Research and Development Program for the United States Department of Interior (1970).
- (28) Tinsley, J. L. and Jordan, R. B. "Stress Urine Testosterone Available as Clear Spot," ACRAC Transmissions, 21, 45-51 (1970).
- (29) Siegel, S. and Nunnally, J. C. Theoretical Statistics. McGraw-Hill Book Company, New York (1970).
- (30) Siegel, S. and Nunnally, J. C. Analysis of Variance and Some Related Topics. McGraw-Hill Book Company, New York (1971).
- (31) Siegel, S. and Nunnally, J. C. "Stress and Stool Testosterone in Rhesus Macaques of Various Types," Stress Magazine, 11:20, 19-22 (1970).
- (32) Lichten, S. S., Denny, S. B. and Mills, A. F. Transfer Functions. McGraw-Hill Book Company, New York (1974).
- (33) Fisher, R. A. Personal communication.
- (34) Fienberg, S., Lofter, R. S. and Willett, J. B. Applied Statistics. McGraw-Hill Book Company, New York (1974).
- (35) Goss, R. B. "Chemical Origin of Color," Journal of Chemical Education, 33:20, 418-424 (1956).
- (36) Tykocnik, E. Chemistry of Stool in Urine, Vol. II, Academic Press, Inc., New York (1971).
- (37) Tykocnik, E. Chemistry of Stool in Urine, Vol. I, Academic Press, Inc., New York (1971).
- (38) Duffin, J. B. and Redman, W. B. Stool Excretion Test for Pregnancy. John Wiley & Sons, New York (1974).
- (39) Houtman, J. Handbook Handbook for Stool Excretion Test. McGraw-Hill, Research and Development Program, New York (1971).
- (40) Siegel, J. B. and Siegel, F. C. Psychometric Foundations of Stool. John Wiley & Sons, New York (1974).
- (41) ACRAC Handbook of Psychometrics, American Society of Stool, Stool Excretion and Stool Excretion Test, Inc., New York (1971).

- 46. Gohari, A. L. and Morris, R. L. "Performance of Flat-Plate Solar-Heat Exchangers," *Trans. ASME*, **89**(1967), p. 11. C79412.
- 47. Touloukian, Y. E. Thermophysical Properties of Matter, Vol. 1, IFI/Plenum, New York (1971).
- 48. Arpaci, Y. E. Conduction Heat Transfer, Addison-Wesley Publishing Company, Reading, Massachusetts (1966).

BIOGRAPHICAL SKETCH

Ball Ramkrishna Rajwanshi was born in Lucknow, India, on September 12, 1908. After passing his Indian School Certificate exam in 1929, he entered a five-year bachelor's program in mechanical engineering at The Indian Institute of Technology, Roorkee. He obtained his bachelor's degree in mechanical engineering in 1933 and subsequently his master's degree in mechanical engineering from the same institute in 1935. In the same year he was awarded the Government of India National Scholarship for Training Abroad, which made it possible for him to pursue the doctoral work at the University of Florida.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.


Erik A. Taylor, Chairman
Professor of Mechanical Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.


Irving S. Reich, Co-Chairman
Associate Professor of Mechanical Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.


Edwin C. Weaver
Professor of Mechanical Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.


Richard E. Long
Professor of Mechanical Engineering

I certify that this thesis meets the standards and that, in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Arum K. Vyas

Arum K. Vyas
Professor of Mathematics

This dissertation was submitted to the Graduate Faculty of the College of Engineering and to the Graduate Council, and was accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

June 1978

Wayne H. Chen
Prof. College of Engineering

John Graham Smith